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Numerical Seakeeping Predictions Including Interaction Effects Between Two Ships

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DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

Contractor Report

DREA CR 2000-050

April 2000

National Defence Défense nationale

Canada

National Defence
Research and Development Branch

Défense nationale
Bureau de recherche et développement

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Scientific Authority ______ signature on file ______

W7707-8-6038/001/HAL
Contract Number

April 2000

CONTRACTOR REPORT

Prepared for

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

Canada

Numerical Seakeeping Predictions Including Interaction Effects between Two Ships

DREA CR 2000-050

L. Li, Y.J. He, and C.C. Hsiung, Centre for Marine Vessel Development and Research, DalTech, Dalhousie University

Abstract

A modified version of the SHIPINT program, SHIPINT2, has been developed to compute the restraining forces and motions of the two ship interaction problem in accordance with prescribed captive model test conditions. The coupled motions are computed using a three-dimensional panel method with zero forward speed Green's function and a simple forward speed correction. With this method, the field points and source points are distributed on the wetted surface of two ships (ship-a and ship-b). The unsteady hydrodynamic forces, wave exciting forces and coupled motion amplitudes are computed based on the two ships interacting. Two ship double-body flow is used to determine the steady flow disturbance potential and velocity distribution. In this computation, the m-term computation is performed by the integral equation method based on the double body flow of two ships interacting. Alternatively, with the uniform flow assumption, the approximate m-terms can also be used in this study. Schmitke's method is applied to compute the viscous roll damping coefficients for ship-a and ship-b separately. The viscous interaction between the two ships is neglected. Spectral analyses for irregular waves are also carried out for ship-a and ship-b.

Calculations have been carried out in regular waves with heading angles of 120, 150, and 180 degrees for two forward speeds of 12 knots and 0 knots. Also considered is a lateral separation distance of 52.705 m, and a longitudinal separation distance $d_x/L_{ALSC} = 0.25$. Ship motions in irregular waves, using the Bretschneider spectrum for Sea State 6 (H_s = 5.0 m, T_p = 12.4 s), have also been computed.

Résumé

Une version modifiée du programme SHIPINT, appelée SHIPINT2, a été mise au point pour résoudre les problèmes associés au calcul des forces de retenue et des mouvements de deux navires en interaction conformément aux conditions d'essai prescrites sur maquette entravée. Les mouvements conjugués sont calculés à l'aide de la méthode des panneaux à trois dimensions avec la fonction de Green pour une vitesse d'avance nulle et une correction simple de la vitesse d'avance. Cette méthode permet de distribuer les points de parcours et les points de source sur la surface mouillée des deux navires (navire a et navire b). Le calcul des forces hydrodynamiques non stationnaires, des forces d'excitation des vagues et de l'amplitude des mouvement conjugués repose sur l'interaction des deux navires. On utilise des paramètres d'écoulement doubles sur deux corps pour déterminer le potentiel de perturbation et la distribution de la vitesse de l'écoulement stationnaire. Le calcul du terme m est effectué par la méthode de l'équation intégrale axée sur l'écoulement double de deux corps (deux navires) en interaction. En

contrepartie, si l'hypothèse de l'écoulement uniforme est retenue, des termes m approximatifs peuvent aussi servir aux fins de l'étude. La méthode Schmitke est employée pour calculer séparément les coefficients d'amortissement en roulis visqueux du navire a et du navire b. L'interaction visqueuse entre les deux navires est négligeable. On a aussi procédé à l'analyse spectrale de vagues irrégulières pour le navire a et pour le navire b.

Des calculs ont été faits dans des vagues régulières avec des angles de cap de 120, 150 et 180 degrés à des vitesses d'avance de 12 nœuds et de 0 nœud. Les autres paramètres de calcul sont une distance de séparation latérale de 52,705 m et une distance de séparation longitudinale de $dx/L_{ALSC} = 0,25$. Les mouvements des navires dans des vagues irrégulières ont aussi été calculés à l'aide du spectre de Bretschneider pour des états de mer de niveau 6 (Hs = 5,0 m, Tp = 12,4 s).

DREA CR 2000-050

NUMERICAL SEAKEEPING PREDICTIONS INCLUDING INTERACTION EFFECTS BETWEEN TWO SHIPS

by

L. Li, Y.J. He, and C.C. Hsiung

EXECUTIVE SUMMARY

Introduction

In anticipation of procurement of new naval supply ships, numerical and experimental studies have examined seakeeping of two ships within close proximity. The ships considered to date have been a concept design of the Afloat Logistic Support Capability (ALSC) and a frigate design similar to the Halifax class. During towing tank tests, the ALSC and frigate models were free in heave, roll, and pitch but were restrained in surge, sway, and yaw. This report describes numerical predictions of motions and restraining forces during the experiments.

Principal Results

The computer program SHIPINT formed the basis for the numerical predictions. It was necessary to modify the program to include the influence of restraining forces in specified modes. The modified program can compute wave-induced motions for unrestrained modes and restraining forces for restrained modes. The report gives comparisons of model motions and restraining forces for cases with each ship alone and for the ships in close proximity.

Significance of Results

The modified computer program SHIPINT2 is a promising tool for prediction of motions for two ships in close proximity. The numerical predictions presented in the report will permit validation with experimental results. The numerical predictions suggest that interaction effects can be significant for a smaller ship operating in the vicinity of a larger ship.

Future Plans

A report of experimental results will include comparisons with the present numerical predictions. These comparisons will be used to examine the validity of SHIPINT2 and to identify areas for improvement. The numerical model could be used in future studies of replenishment-at-sea.

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List of Figures

Nomenclature

A_w^a	waterplane area of ship-a
A_w^b	waterplane area of ship-b
B	beam of ship
B_a	beam of ship-a
B_b	beam of ship-b
C_b	block coefficient
C_{jk}^a	restoring force coefficient matrix of ship-a
C_{jk}^b	restoring force coefficient matrix of ship-b
D	volume displacement of ship
dx	longitudinal separation distance of two ships
dy	lateral separation distance between the centerlines of two ships
d_{a1}	radius of inertia of the waterplane of ship-a around the $o_a y_a$-axis
d_{a3}	radius of inertia of the waterplane of ship-a around the $o_a x_a$-axis
d_{b1}	radius of inertia of the waterplane of ship-b around the $o_b y_b$-axis
d_{b3}	radius of inertia of the waterplane of ship-b around the $o_b x_b$-axis
f_j^{Raa}	time independent radiated force on ship-a due to the oscillation of ship-a itself while ship-b is at rest
f_j^{Rab}	time independent radiated force on ship-a due to the oscillation of ship-b while ship-a is at rest

f_j^{Rbb}	time independent radiated force on ship-b due to the oscillation of ship-b itself while ship-a is at rest
f_j^{Rba}	time independent radiated force on ship-b due to the oscillation of ship-a while ship-b is at rest
F_j^{a}	time dependent hydrodynamic force acting on ship-a
F_j^{b}	time dependent hydrodynamic force acting on ship-b
F_j^{aS}	hydrostatic force acting on ship-a
F_j^{bS}	hydrostatic force acting on ship-b
f_j^{Ra}	time independent radiated force on ship-a, $f_j^{Ra} = f_j^{Raa} + f_j^{Rba}$
f_j^{Rb}	time independent radiated force on ship-b, $f_j^{Ra} = f_j^{Rab} + f_j^{Rbb}$
f_j^{Da}	time independent diffracted force on ship-a
f_j^{Db}	time independent diffracted force on ship-b
f_j^{Ia}	time independent incident wave force on ship-a
f_j^{Ib}	time independent incident wave force on ship-b
f_j^{Wa}	time independent wave exciting force on ship-a, $f_j^{Wa} = f_j^{Ia} + f_j^{Ra} + f_j^{Da}$
f_j^{Wb}	time independent wave exciting force on ship-b, $f_j^{Wb} = f_j^{Ib} + f_j^{Rb} + f_j^{Db}$
F_j^{Ra}	time dependent radiated force on ship-a, $F_j^{Ra} = F_j^{Raa} + F_j^{Rba}$
F_j^{Rb}	time dependent radiated force on ship-b, $F_j^{Ra} = F_j^{Rab} + F_j^{Rbb}$
F_j^{Da}	time dependent diffracted force on ship-a
F_j^{Db}	time dependent diffracted force on ship-b
F_j^{Ia}	time dependent incident wave force on ship-a
F_j^{Ib}	time dependent incident wave force on ship-b
F_j^{Wa}	time dependent wave exciting force on ship-a, $F_j^{Wa} = F_j^{Ia} + F_j^{Da}$

F_j^{Wb}	time dependent wave exciting force on ship-b. $F_j^{Wb} = F_j^{Ib} + F_j^{Db}$
F_1	measurement surge force amplitude
F_2	measurement sway force amplitude
F_3	measurement heave force amplitude
$G, \overline{G}, \hat{G}$	Green's Functions
g	gravitational acceleration
Gy	lateral separation gap of two ships, $Gy = dx - 1/2(B_a + B_b)$
I_{jk}^a	moments of inertia of ship-a, j,k=1,2,3
I_{jk}^b	moments of inertia of ship-b, j,k=1,2,3
K	wave number
L	ship length between perpendiculars
L_a	ship-a length between perpendiculars
L_b	ship-b length between perpendiculars
m_j	m-terms, j=1,2,3,...,6
m_j^a	m-terms of ship-a, j=1,2,3,...,6
m_j^b	m-terms of ship-b, j=1,2,3,...,6
m_{jk}^a	generalized mass matrix of ship-a, j,k=1,2,3,...,6
m_{jk}^b	generalized mass matrix of ship-b, j,k=1,2,3,...,6
M^a	mass of ship-a
M^b	mass of ship-b
M_4	measurement roll force amplitude
M_5	measurement pitch force amplitude

M_6	measurement yaw force amplitude
$\vec{n}^a$	unit normal vector on wetted surface of ship-a pointing into the fluid
$\vec{n}^b$	unit normal vector on wetted surface of ship-b pointing into the fluid
n_j^a	generalized unit normal on wetted surface of ship-a, j=1,2,3,...,6
n_j^b	generalized unit normal on wetted surface of ship-a, j=1,2,3,...,6
oxyz	steady moving coordinate system
$o_a x_a y_a z_a$	ship-fixed coordinate system of ship-a
$o_b x_b y_b z_b$	ship-fixed coordinate system of ship-b
p	pressure
$p(x, y, z)$	field point
$q(\xi, \eta, \zeta)$	source point
Rxx	roll radius of gyration of the ship for ship-a in $o_a x_a y_a z_a$ coordinate system for ship-b in $o_b x_b y_b z_b$ coordinate system
Ryy	pitch radius of gyration of the ship for ship-a in $o_a x_a y_a z_a$ coordinate system for ship-b in $o_b x_b y_b z_b$ coordinate system
Rzz	yaw radius of gyration of the ship for ship-a in $o_a x_a y_a z_a$ coordinate system for ship-b in $o_b x_b y_b z_b$ coordinate system
$\vec{r}_a$	position vector from the centre of gravity of ship-a to a point $p(x_a, y_a, z_a)$ on the ship hull surface
$\vec{r}_b$	position vector from the centre of gravity of ship-b to a point $p(x_b, y_b, z_b)$ on the ship hull surface
$\vec{r}_g$	position vector from the centre of gravity of a ship to a point $p(x, y, z)$ on the ship hull surface
S_a	mean wetted surface of ship-a

S_b	mean wetted surface of ship-b
T	draft of a ship
T_1	modal period
T_p	peak wave period
t	time
U	steady forward speed of a ship
W	steady flow velocity, $W = \nabla(-Ux + \phi_s)$
x_1^a, x_1^b	surge motion of ship-a and ship-b
x_2^a, x_2^b	sway motion of ship-a and ship-b
x_3^a, x_3^b	heave motion of ship-a and ship-b
x_4^a, x_4^b	roll motion of ship-a and ship-b
x_5^a, x_5^b	pitch motion of ship-a and ship-b
x_6^a, x_6^b	yaw motion of ship-a and ship-b
(x_g^a, y_g^a, z_g^a)	coordinate of centre of gravity of ship-a in $o_a x_a y_a z_a$
(x_g^b, y_g^b, z_g^b)	coordinate of centre of gravity of ship-b in $o_b x_b y_b z_b$
$\bar{x}_k^a, \bar{x}_k^b$	time independent motion amplitudes of ship-a and ship-b, k=1,2,...,6
$\bar{x}_f^a$	x-coordinate of the centre of the floatation of ship-a
$\bar{x}_f^b$	x-coordinate of the centre of the floatation of ship-b
$\dot{x}_k^a$	velocity of ship-a, k=1,2,3 translation; k=4,5,6 rotation
$\dot{x}_k^b$	velocity of ship-b, k=1,2,3 translation; k=4,5,6 rotation
$\ddot{x}_k^a$	acceleration of ship-a, k=1,2,3 translation; k=4,5,6 rotation
$\ddot{x}_k^b$	acceleration of ship-b, k=1,2,3 translation; k=4,5,6 rotation

z_B^a	z-coordinate of the centre of bouyancy of ship-a in $o_a x_a y_a z_a$
z_B^b	z-coordinate of the centre of bouyancy of ship-b in $o_b x_b y_b z_b$
β	angle between the wave propagation direction and the x-axis $\beta = 180°$ for head seas
$\triangle^a$	displacement of ship-a
$\triangle^b$	displacement of ship-b
ζ_a	incident wave amplitude
ξ_1	surge motion amplitude
ξ_2	sway motion amplitude
ξ_3	heave motion amplitude
ξ_4	roll motion amplitude
ξ_5	pitch motion amplitude
ξ_6	yaw motion amplitude
λ	incident wave length
λ_{jk}^{aa}	damping coefficient of ship-a due to the motion of ship-a while ship-b is at rest
λ_{jk}^{ab}	damping coefficient of ship-a due to the motion of ship-b. while ship-a is at rest
λ_{jk}^{bb}	damping coefficient of ship-b due to the motion of ship-b while ship-a is at rest
λ_{jk}^{ba}	damping coefficient of ship-b due to the motion of ship-a while ship-b is at rest
μ_{jk}^{aa}	added mass of ship-a due to the motion of ship-a while ship-b is at rest
μ_{jk}^{ab}	added mass of ship-a due to the motion of ship-b while ship-a is at rest

μ_{jk}^{bb}	added mass of ship-b due to the motion of ship-b while ship-a is at rest
μ_{jk}^{ba}	added mass of ship-b due to the motion of ship-a while ship-b is at rest
ν	wave number $= \omega^2/g$
ν_e	encounter wave number, $\nu_e = \omega_e^2/g$
ρ	water density
σ_S^a	steady flow source density on ship-a
σ_S^b	steady flow source density on ship-b
σ_D^a	diffraction source density on ship-a
σ_D^b	diffraction source density on ship-b
σ_k^{aa}	radiation source density on ship-a due to the motion of ship -a while ship-b is at rest
σ_k^{ab}	radiation source density on ship-a due to the motion of ship -b while ship-a is at rest
σ_k^{ba}	radiation source density on ship-b due to the motion of ship -a while ship-b is at rest
σ_k^{bb}	radiation source density on ship-b due to the motion of ship -b while ship-b is at rest
Φ	time dependent unsteady velocity potential
Φ_S	steady velocity potential, $\Phi_S = -Ux + \phi_s$
Φ_D	time dependent diffracted wave velocity potential
ϕ_D	time independent diffracted wave velocity potential
Φ_I	time dependent incident wave velocity potential
ϕ_I	time independent incident wave velocity potential
ϕ_k	canonical radiated wave velocity potential

ϕ_k^a	the radiated wave potential of k^{th} direction, $k = 1, 2, ..., 6$ due to the oscillation of ship-a while ship-b is at rest
ϕ_k^b	the radiated wave potential of k^{th} direction, $k = 1, 2, ..., 6$ due to the oscillation of ship-b while ship-a is at rest
Φ_R^a	time dependent radiated wave velocity potential of ship-a
Φ_R^b	time dependent radiated wave velocity potential of ship-b
ϕ_R	time independent radiated wave velocity potential
Φ_R	time dependent radiated wave velocity potential
Φ_T	time dependent total wave velocity potential
ϕ_s	steady disturbance velocity potential
Φ_R^a	time dependent radiated wave velocity potential of ship-a
ω	incident wave frequency
ω_e	frequency of wave encounter

Summary

A modified version of the SHIPINT program, SHIPINT22, has been developed to compute the restraining forces and motions of the two ship interaction problem in accordance with prescribed captive model test conditions. The coupled motions are computed using a three-dimensional panel method with zero forward speed Green's function and a simple forward speed correction. With this method, the field points and source points are distributed on the wetted surface of two ships (ship-a and ship-b). The unsteady hydrodynamic forces, wave exciting forces and coupled motion amplitudes are computed based on the two ships interacting. Two ship double-body flow is used to determine the steady flow disturbance potential and velocity distribution. In this computation, the m-term computation is performed by the integral equation method based on the double body flow of two ships interacting. Alternatively, with the uniform flow assumption, the approximate m-terms can also be used in this study. Schmitke's method is applied to compute the viscous roll damping coefficients for ship-a and ship-b, separately. The viscous interaction between the two ships is neglected. Spectral analyses for irregular waves are also carried out for ship-a and ship-b.

Calculations have been carried out in regular waves with heading angles of 120^o, 150^o and 180^o for two forward speeds of 12 knots and 0 knots. Also considered is a lateral separation distance of $52.705m$, and a longitudinal separation distance $d_x/L_{ALSC} = 0.25$. Ship motions in irregular waves, using the Bretschneider spectrum for Sea State 6($H_s = 5.0m$ and $T_p = 12.4s$), have also been computed.

1 Introduction

In support of the procurement of the Afloat Logistics Support Capability (ALSC), a series of model tests is going to be conducted at the Institute for Marine Dynamics (IMD) to examine motions in waves of the ALSC and a frigate in close proximity.

In 1996, the Centre for Marine Vessel Development and Research (CMVDR) developed a computer program SHIPINT that predicts the motions of two ships involved in RAS operations. The original SHIPINT program computes the motions of two ships that are in free running modes without restraining forces. In order to use the model test results to validate the SHIPINT program, a new version of the program was needed to include the predictions for the model test conditions.

This report describes the work of the numerical seakeeping predictions project carried out by CMVDR for Defense Research Establishment Atlantic (DREA).

According to the project requirements, CMVDR was to provide numerical simulation results in accordance with model test cases that will be conducted at IMD for two ships interacting in waves. The model test cases have been well defined in the contract. CMVDR needed to modify the existing SHIPINT code to simulate the model test cases. This required making the existing SHIPINT code more flexible, so that each mode of motion of either ship can be restrained at the user's will. The task has been performed by adding a numerical switch in the program. The control parameters are specified in the input file *shipint.in* and the output format is modified to reflect the simulation results.

Hulls of the ALSC and the SCAN frigate have been panelized and viscous damping calculations have been prepared. Both ships can be restrained in certain specified modes of motion. A new module to calculate the radiation forces due to the unrestrained ship as well as the forces due to the remaining unrestrained motion of the other ship has been formulated and implemented. This report presents the simulation results corresponding to the intended test conditions.

2 Description of the Problem

In this study, two ships assumed to be rigid bodies, advancing with the same forward speed and heading in waves, are considered. It is also assumed that the two ships oscillate harmonically in time about their mean positions. Based on linear potential theory, the flow field will be a superposition of steady flow, incident wave, diffracted wave and radiated wave. The steady flow effect on the ship motion will be in the form of m-terms and is also considered in the unsteady force computations. Similar to the SHIPINT program developed for DREA [1][2], we use the following assumptions and solution methods.

2.1 Basic assumptions

We assumed that:

1. The fluid is inviscid, incompressible, and the flow is irrotational;
2. The linear free surface condition and small amplitude motions are considered;
3. The double-body steady flow model (solid free surface) is adopted; thus, the steady wave-making effect is neglected;
4. A zero-speed Green's function is employed, i.e. $U\frac{\partial}{\partial x} << \omega_e$;
5. The waterline integration term is ignored; and
6. The ships are moving in regular waves.

2.2 Solution methods

The solution methods consist of:

1. A 3-D panel Green's function method for the two ship coupled motions; and
2. A double-body flow method (the Hess-Smith method) for the m-terms and steady flow computations.

2.3 Formulation of the problem

To validate the computer program, we numerically simulated the model test conditions so that the computated results from the SHIPINT program can be directly compared with the model test results.

The problem of two ships interacting in waves can be described as two rigid bodies advancing in the same direction with a constant speed. The mathematical formulation of this problem is based on the same assumptions as in the previous reports[1][2]. The coordinate systems $o - xyz$, $o_a - x_a y_a z_a$ and $o_b - x_b y_b z_b$ are translating with the ships at a steady forward speed U, as shown in

Fig.1. The origins o_a and o_b are located at the centre of gravity of ship-a and ship-b, respectively. The z-axis is positive upward and o-xy is on the calm water surface. The regular incident waves make an angle β with the positive ox axis.

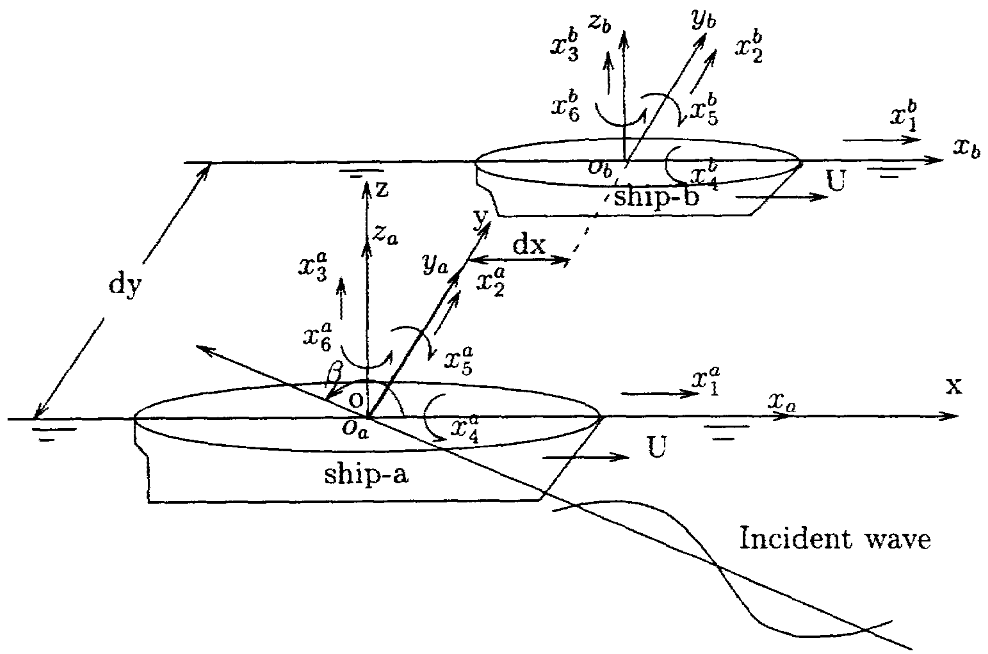


Figure 1: Coordinate Systems

As we assume that the ships are rigid bodies, the motions of the ships must satisfy Newton's second law:

$$m^a_{jk}\ddot{x}^a_k = F^{Wa}_j + F^{Ra}_j + F^{Sa}_j \tag{1}$$

$$m^b_{jk}\ddot{x}^b_k = F^{Wb}_j + F^{Rb}_j + F^{Sb}_j \tag{2}$$

where m^a_{jk} is the mass matrix of ship-a. m^b_{jk} is the mass matrix of ship-b; $\ddot{x}^a_k = Re[-\omega^2\bar{x}^a_k e^{-i\omega t}]$ is the acceleration of ship-a; $\ddot{x}^b_k = Re[-\omega_e^2\bar{x}^b_k e^{-i\omega_e t}]$ is the acceleration of ship-b; F^{Wa}_j and F^{Wb}_j are the wave exciting forces on ship-a and ship-b, respectively; and F^{Ra}_j and F^{Rb}_j are the radiation forces on ship-a and ship-b, respectively. F^{Sa}_j and F^{Sb}_j are the hydrostatic forces on ship-a and ship-b, respectively.

After solving the boundary value problems using potential flow theory, we are able to rewrite the equations of motion in the following forms:

$$\sum_{k=1}^{6}[-\omega_e^2(m^a_{jk}+\mu^{aa}_{j,k}) - i\omega_e\lambda^{aa}_{jk} + C^a_{jk}]\bar{x}^a_k + [-\omega_e^2\mu^{ab}_{j,k} - i\omega_e\lambda^{ab}_{jk}]\bar{x}^b_k = f^{Wa}_j \tag{3}$$

$$\sum_{k=1}^{6}[-\omega_e^2\mu_{j,k}^{ba} - i\omega_e\lambda_{jk}^{ba}]\bar{x}_k^a + [-\omega_e^2(m_{jk}^b + \mu_{j,k}^{bb}) - i\omega_e\lambda_{jk}^{bb} + C_{jk}^b]\bar{x}_k^b = f_j^{Wb} \quad (4)$$

where
C_{jk}^a = restoring force coefficient matrix of ship-a
C_{jk}^b = restoring force coefficient matrix of ship-b
$\bar{x}_k^a$ = complex motion amplitudes of ship-a
$\bar{x}_k^b$ = complex motion amplitudes of ship-b

Furthermore, μ_{jk}^{aa} is the added mass of ship-a due to the motion of ship-a; μ_{jk}^{ab} is the added mass of ship-a due to the motion of ship-b; λ_{jk}^{aa} is the damping coefficient of ship-a due to the motion of ship-a; and λ_{jk}^{ab} is the damping coefficient of ship-a due to the motion of ship-b:

$$\mu_{jk}^{aa} = \rho\Big\{\int\int_{S_a} Re[\phi_k^a]n_j dS + \frac{U}{\omega_e}\int\int_{S_a} Im[\frac{\partial\phi_k^a}{\partial x}]n_j dS - \frac{1}{\omega_e}\int\int_{S_a} Im[\nabla\phi_k^a\cdot\nabla\phi_s]n_j dS\Big\} \quad (5)$$

$$\mu_{jk}^{ab} = \rho\Big\{\int\int_{S_a} Re[\phi_k^b]n_j dS + \frac{U}{\omega_e}\int\int_{S_a} Im[\frac{\partial\phi_k^b}{\partial x}]n_j dS - \frac{1}{\omega_e}\int\int_{S_a} Im[\nabla\phi_k^b\cdot\nabla\phi_s]n_j dS\Big\} \quad (6)$$

$$\lambda_{jk}^{aa} = \rho\Big\{\omega_e\int\int_{S_a} Im[\phi_k^a]n_j dS - U\int\int_{S_a} Re[\frac{\partial\phi_k^a}{\partial x}]n_j dS + \int\int_{S_a} Re[\nabla\phi_k^a\cdot\nabla\phi_s]n_j dS\Big\} \quad (7)$$

$$\lambda_{jk}^{ab} = \rho\Big\{\omega_e\int\int_{S_a} Im[\phi_k^b]n_j dS - U\int\int_{S_a} Re[\frac{\partial\phi_k^b}{\partial x}]n_j dS + \int\int_{S_a} Re[\nabla\phi_k^b\cdot\nabla\phi_s]n_j dS\Big\} \quad (8)$$

In the following equations, μ_{jk}^{bb} is the added mass of ship-b due to the motion of ship-b; μ_{jk}^{ba} is the added mass of ship-b due to the motion of ship-a; λ_{jk}^{bb} is the damping coefficient of ship-b due to the motion of ship-b; and λ_{jk}^{ba} is the damping coefficient of ship-b due to the motion of ship-a:

$$\mu_{jk}^{bb} = \rho\Big\{\int\int_{S_b} Re[\phi_k^b]n_j dS + \frac{U}{\omega_e}\int\int_{S_b} Im\frac{\partial\phi_k^b}{\partial x}]n_j dS - \frac{1}{\omega_e}\int\int_{S_b} Im[\nabla\phi_k^b\cdot\nabla\phi_s]n_j dS\Big\} \quad (9)$$

$$\mu_{jk}^{ba} = \rho\Big\{\int\int_{S_b} Re[\phi_k^a]n_j dS + \frac{U}{\omega_e}\int\int_{S_b} Im[\frac{\partial\phi_k^a}{\partial x}]n_j dS - \frac{1}{\omega_e}\int\int_{S_b} Im[\nabla\phi_k^a\cdot\nabla\phi_s]n_j dS\Big\} \quad (10)$$

$$\lambda_{jk}^{bb} = \rho\Big\{\omega_e\int\int_{S_b} Im[\phi_k^b]n_j dS - U\int\int_{S_b} Re[\frac{\partial\phi_k^b}{\partial x}]n_j dS + \int\int_{S_b} Re[\nabla\phi_k^b\cdot\nabla\phi_s]n_j dS\Big\} \quad (11)$$

$$\lambda_{jk}^{ba} = \rho\Big\{\omega_e\int\int_{S_b} Im[\phi_k^a]n_j dS - U\int\int_{S_b} Re[\frac{\partial\phi_k^a}{\partial x}]n_j dS + \int\int_{S_b} Re[\nabla\phi_k^a\cdot\nabla\phi_s]n_j dS\Big\} \quad (12)$$

Please refer to reference [1] for more details.

3 Motions and Forces in Restrained Modes

3.1 Restrained motion and force components

When the motion of a ship is restrained in certain modes of motion, the actual motion displacements should be zero in those particular modes. In order to simulate this effect, the equations of motion are rewritten in the following form:

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^a \bar{x}_k^a) = \sum_{k=1}^{6}[(\omega_e^2 \mu_{j,k}^{aa} + i\omega_e \lambda_{jk}^{aa}]\bar{x}_k^a - \sum_{k=1}^{6} C_{jk}^a \bar{x}_k^a + \sum_{k=1}^{6}[\omega_e^2 \mu_{j,k}^{ab} + i\omega_e \lambda_{jk}^{ab}]\bar{x}_k^b + f_j^{Wa} \quad (13)$$

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^b \bar{x}_k^b) = \sum_{k=1}^{6}[(\omega_e^2 \mu_{j,k}^{bb} + i\omega_e \lambda_{jk}^{bb}]\bar{x}_k^b - \sum_{k=1}^{6} C_{jk}^b \bar{x}_k^b + \sum_{k=1}^{6}[\omega_e^2 \mu_{j,k}^{ba} + i\omega_e \lambda_{jk}^{ba}]\bar{x}_k^a + f_j^{Wb} \quad (14)$$

If we further examine the right-hand side of the above equations, it is understood that the first terms of equations (15) and (16) represent the radiation forces on ship-a, f_j^{Raa}, and ship-b, f_j^{Rbb}, due to the oscillatory motions of ship-a or ship-b itself. The second terms are the hydrostatic restoring forces, f_j^{Sa} for ship-a and f_j^{Sb} for ship-b, and the third terms are the radiation forces, f_j^{Rba}, f_j^{Rba}, due to the oscillatory motion effect of the other ship. The last terms are the wave exciting forces, f_j^{Wa} and f_j^{Wb}. Then we can rewrite equations (13) and (14) as:

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^a \bar{x}_k^a) = f_j^{Raa} + f_j^{Sa} + f_j^{Rab} + f_j^{Wa} \quad (15)$$

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^b \bar{x}_k^b) = f_j^{Rbb} + f_j^{Sb} + f_j^{Rba} + f_j^{Wb} \quad (16)$$

When conducting model tests, we usually measure the forces for the j^{th} mode of motion as F_j^{Ma} for ship-a and F_j^{Mb} for ship-b, by restraining the j^{th} mode of motion. The equations of motion for the model test then become:

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^a \bar{x}_k^a) = F_j^{Ma} \quad (17)$$

$$\sum_{k=1}^{6}(-\omega_e^2 m_{jk}^b \bar{x}_k^b) = F_j^{Mb} \quad (18)$$

Therefore, the measured forces on ship-a and ship-b should be:

$$F_j^{Ma} = f_j^{Raa} + f_j^{Sa} + f_j^{Rab} + f_j^{Wa} \quad (19)$$

$$F_j^{Mb} = f_j^{Rbb} + f_j^{Sb} + f_j^{Rba} + f_j^{Wb} \quad (20)$$

Thus the force measurement on each ship contains four components. If the motions in certain modes are restrained in a model test, the values of the force components will be changed and the sum of all components in that restrained mode is called the restraining force. In the following section, we will discuss how the restrained motion will affect each force component and how the restraining forces and motions are computed.

3.2 Analysis of the restrained motion problem

In a captive model test, the oscillatory motions in certain modes of a model may be restrained in order to measure the forces, while the motions in the remaining modes may not be restrained. In the case of a totally restrained mode, the model will not be able to oscillate. However, in the earlier SHIPINT code, the ship is free to move in any mode. Therefore, it is desirable to restrain the motions of a ship (or both ships) in any mode as specified. In formulating the two-ship interaction problem, ships are assumed to be fixed for the computations of the diffracted and incident wave problem. Only the radiation problem involves the oscillatory motion of the ships. Therefore, the motion of the ship(s) should be able to be restrained in certain modes in order to simulate the model test condition.

In the case of two ships freely oscillating in waves, the radiated waves are generated by the oscillation of both ships. The radiation waves of a ship are not only caused by the oscillation of itself but also by the oscillation of the other ship. This is a rather complicated situation. Since the the motion is restrained, the velocity potential is zero in the restrained mode, and therefore, the added mass and damping coefficients in that mode are zero. However, this does not mean that the radiation force is zero. The other ship (if not restrained) and the radiation waves of the ship itself free to move in the remaining modes could generate radiation forces.

Considering the case, for example, of the motion of ship-a restrained in the j_a^{th} mode. The velocity potential per unit velocity in the k^{th} mode of motion of ship-a can be found by solving the following boundary value problem:

$$
\begin{aligned}
&\nabla^2 \phi_k^a = 0 \\
&(g\frac{\partial}{\partial z} + U^2\frac{\partial^2}{\partial x^2} + 2i\omega_e U\frac{\partial}{\partial x} - \omega_e^2)\phi_k^a = 0 \qquad (z=0) \\
&\frac{\partial \phi_k^a}{\partial n}\,|_{S_a} = n_k^a - \frac{m_k^a}{i\omega_e} \\
&\frac{\partial \phi_k^a}{\partial n}\,|_{S_b} = 0 \\
&\frac{\partial \phi_k^a}{\partial n}\,|_{z\to-\infty} = 0 \\
&\textit{and the radiation condition}: \textit{ outgoing ring waves}
\end{aligned}
\tag{21}
$$

where S_a is the hull surface of ship-a; S_b is the hull surface of ship-b; ω_e is the frequency of encounter; k is the index of the mode of motion (k=1,2, ..., 6); n_k^a is the generalized unit inner normal of ship-a; U is the ship steady forward speed; and g is the gravitational acceleration. Furthermore, m_k^a is the m-term of ship-a in the k^{th} mode, and is the steady flow effect on the radiation waves of ship-a.

If the motion in the j_a^{th} mode is restrained, the boundary condition on ship-a (the third equation of(21)) would be zero and therefore the solution of the radiation potential in the j_a^{th} mode will be zero. Hence we are concerned about the radiation problem in the unrestrained modes. This has

been implemented in the program by providing an automatical switch between the modes. Similarly, if the motion of ship-b is restrained in the j_b^{th} mode, we will only need the radiation potentials of remaining unrestrained modes. Once the radiation potentials are obtained, we can compute the radiation forces. Even though there is no oscillatory motion in the restrained mode, there still may exists radiation forces in this mode due to the contributions of the other ship's radiation waves or radiation waves due to unrestrained modes of motion of the same ship.

3.3 Restrained radiation forces

The radiation force in the jth mode acting on ship-a is given by:

$$F_j^{Ra}(x,y,z,t) = Re[f_j^{Ra} e^{-i\omega_e t}] \tag{22}$$

where $f_j^{Ra} = f_j^{Ra}(x,y,z)$ is the time independent spatial radiation force in the jth mode on ship-a, and

$$f_j^{Ra} = f_j^{Raa} + f_j^{Rab} \tag{23}$$

where f_j^{Raa} is the radiation force on ship-a due to the oscillation of ship-a with ship-b fixed without oscillation; and f_j^{Rab} is the radiation force on ship-a due to the oscillation of ship-b with ship-a fixed.

By substituting the radiation potential of ship-a and introducing added mass and damping coefficients (see equations (5)-(12)), the radiation force can be expressed as:

$$\begin{aligned} f_j^{Raa} &= \sum_{k=1}^{6}[-\ddot{x}_k^a \mu_{jk}^{aa} - \dot{x}_k^a \lambda_{jk}^{aa}] \\ f_j^{Rab} &= \sum_{k=1}^{6}[-\ddot{x}_k^b \mu_{jk}^{ab} - \dot{x}_k^b \lambda_{jk}^{ab}] \end{aligned} \tag{24}$$

Similarly, the time independent spatial radiation force acting on ship-b is:

$$f_j^{Rb} = f_j^{Rbb} + f_j^{Rba} \tag{25}$$

with

$$\begin{aligned} f_j^{Rbb} &= \sum_{k=1}^{6}[-\ddot{x}_k^a \mu_{jk}^{bb} - \dot{x}_k^b \lambda_{jk}^{bb}] \\ f_j^{Rba} &= \sum_{k=1}^{6}[-\ddot{x}_k^b \mu_{jk}^{ba} - \dot{x}_k^a \lambda_{jk}^{ba}] \end{aligned} \tag{26}$$

and f_j^{Rbb} is the radiation force on ship-b due to the oscillation of ship-b, with ship-a fixed without oscillation; and f_j^{Rba} is the radiation force on ship-b due to the oscillation of ship-a, with ship-b fixed.

3.4 Restrained wave exciting forces

Since the wave exciting forces are not generated by the ship motion, the restrained wave exciting forces will be the same as the wave exciting forces that have been computed by solving the diffraction and incident wave problems as in the previous SHIPINT code.

3.5 Restrained restoring forces

The restoring forces depend on the motion displacements. If the motion of a ship is restrained in the jth mode, there will be no motion displacement in that mode and therefore, the restoring force should be zero. However, since the ship is not symmetric to all planes, there might be restoring force components in the restrained modes. The restoring forces are computed based on this consideration.

3.6 Computation of unrestrained motions of the restrained hull

For a restrained hull, there is no motion in the restrained modes. If N_r is the number of restrained modes, then when solving motions of the restrained hull, the number of unknown complex motion displacements $\bar{x}_k$ will be $(12 - N_r)$. The program has been modified to solve automatically for the motions of the restrained hull in the unrestrained modes.

3.7 Computation of restrained force components

The following steps are followed to compute the restrained radiation forces and restoring forces:

1. Solve the radiation problem and use the computed radiation potential to calculate the added mass and damping coefficients:
   $\mu^{aa}_{j,k}, \lambda^{aa}_{jk}, \mu^{ab}_{j,k}, \lambda^{ab}_{jk}, \mu^{bb}_{j,k}, \lambda^{bb}_{jk}, \mu^{ba}_{j,k}, and \lambda^{ba}_{jk}.$

2. Solve the equations of motion (3) and (4) for $\bar{x}^a_j$ and $\bar{x}^b_j$ in the unrestrained modes only.

3. Compute the restrained radiation force components:
   $f^{Raa}_j = \sum_{k=1}^{6}[(\omega_e^2\mu^{aa}_{j,k} + i\omega_e\lambda^{aa}_{jk}]\bar{x}^a_k$
   $f^{Rab}_j = \sum_{k=1}^{6}[\omega_e^2\mu^{ab}_{j,k} + i\omega_e\lambda^{ab}_{jk}]\bar{x}^b_k$
   $f^{Rbb}_j = \sum_{k=1}^{6}[(\omega_e^2\mu^{bb}_{j,k} + i\omega_e\lambda^{bb}_{jk}]\bar{x}^b_k$
   $f^{Rba}_j = \sum_{k=1}^{6}[\omega_e^2\mu^{ba}_{j,k} + i\omega_e\lambda^{ba}_{jk}]\bar{x}^a_k$

4. Compute the restrained restoring forces
   $f^{Sa}_j = \sum_{k=1}^{6} C^a_{jk}\bar{x}^a_k$
   $f^{Sb}_j = \sum_{k=1}^{6} C^b_{jk}\bar{x}^b_k$

The sum of the restrained radiation forces, restoring force and wave exciting forces gives the total force that corresponds to the force measurement in the model test.

4 Code Modifications

SHIPINT22 is a new version of the SHIPINT program with modifications decribed in the following sections:

4.1 Input

The input file *shipint.in* is modified with two extra lines added, one for each ship. Each line contains 6 integer parameters I_j, with $j = 1, 2, ..., 6$ representing the six modes of motions. $I_j = 0$ means no restriction in the j^{th} mode, and $I_j = 1$ correponds to the jth mode being restrained. For example, if the I_j values are given

$$\begin{array}{ll} ship - a: & 1\ 1\ 0\ 0\ 0\ 1 \\ ship - b: & 0\ 0\ 0\ 0\ 0\ 0 \end{array}$$

then for ship-a the surge, sway and yaw motions are restrained but heave, roll and pitch are not restrained; whereas ship-b has all 6 degrees of freedom of motions.

In this way, the user can control and have the flexibility to set-up restrains for any modes of motions of the two ships. An example input file *shipint.in* is shown below:

```
'Dec. 6, 1999'
'ALSC' 'alsc.panel'
180 30.633 8.5 27535 0.588
-1.688 0 3.925
8.047 45 45
1 1 0 0 0 1
'SCAN' 'scan.panel'
122 14.78 4.50 3925.54 0.484
3.284 0.0 2.06
4.921 30.5 30.5
1 1 0 0 0 1
2022.705 0.0
0.0
1
180.
7
0.25
0.5
0.75
1.0
1.25
1.5
2.0
1 1
```

4.2 Numerical switch

Numerical switches are added in the code to reflect the restrained motions and control the following:

- Solution of the solved radiated wave problem depending on the input restraining parameter values;
- Calculation of the restrained forces based on the input restraining parameters;
- Calculation of the motions based on the input restraining parameters; and
- Results based on the input restraining parameters.

4.3 Phase angles for motions and forces

According to the work requirement, the phase angles of ALSC for motions and forces are modified to be referenced to the center of gravity of the ALSC instead of the midship section of the ALSC, the phase angles of SCAN Frigate for motions and forces are modified to be referenced to the center of gravity of the SCAN Frigate. Details of the phase angle shifts are commented in subroutine **af4** of the code.

4.4 Restraining force module

A new module has been written for computing the total restraining forces (i.e. the measured forces in model tests as part of the results of the output). The restrained radiation force components are calculated from the added mass, damping coefficients and the motion displacements. The restoring forces and the wave exciting forces are then added into the radiated forces to form the total restraining forces as follows:

$$F_j^{Ma} = \sum_{k=1}^{6}[(\omega_e^2\mu_{j,k}^{aa} + i\omega_e\lambda_{jk}^{aa}]\bar{x}_k^a - \sum_{k=1}^{6} C_{jk}^a\bar{x}_k^a + \sum_{k=1}^{6}[\omega_e^2\mu_{j,k}^{ab} + i\omega_e\lambda_{jk}^{ab}]\bar{x}_k^b + f_j^{Wa} \tag{27}$$

$$F_j^{Mb} = \sum_{k=1}^{6}[(\omega_e^2\mu_{j,k}^{bb} + i\omega_e\lambda_{jk}^{bb}]\bar{x}_k^b - \sum_{k=1}^{6} C_{jk}^b\bar{x}_k^b + \sum_{k=1}^{6}[\omega_e^2\mu_{j,k}^{ba} + i\omega_e\lambda_{jk}^{ba}]\bar{x}_k^a + f_j^{Wb} \tag{28}$$

where F_j^{Ma} are the total forces on ship_a (i.e. the measured forces of ship_a); F_j^{Mb} are the total forces on ship_b (i.e. the measured forces of ship_b);

For more details see Section 3.

corresponding to the unrestrained modes need to be solved.

4.6 Output

The output modules are modified to include the wave exciting force, computed total restraining forces(measured forces), motion displacements, RMS displacements and accelerations of the two ships (see electronic format Excel files). A new module for formulating the output result of the restraining forces and phase angles is added in the code. For unrestrained modes, the output restraining force components are set to zero and the phase angles are set to "999" or "0" strings which have no physical meanings. The lateral separation gap is also defined and included in the output.

5 Computed Results of Two Naval Ships: the ALSC and the SCAN frigate

5.1 Discretization of ship hulls

For both the ALSC and the SCAN frigate , the origin of the panelization coordinate system is located on the baseline at the ship bow, Station 0. The x-axis is positive towards the stern of the ship, and the z-axis is positive upwards. The regular 21 stations are numbered from 0 to 20. Any inserted sections must be numbered in between the regular stations. The bow and stern profiles normally are taken at the first and last section locations, respectively. For details see the User's Guide of *PANELGEN*.

5.1.1 ALSC hull: ship-a

The ALSC hull was panelized using 21 stations and 20 waterlines. The principal dimensions are as follows:

$L = 180.m$
$B = 30.633m$
$T = 8.5m$
$D = 28223.3tonnes$
$Cb = 0.588$
$Xg = -1.688m$, (aft midships)
$Yg = 0.0m$
$Zg = 3.925m$ (relative to the calm waterline)
$Rxx = 8.047m$
$Ryy = 45.0m$
$Rzz = 45.0m$

The ALSC hull is panelized using *PANELGEN*, an automatic panelization program. The panelized ALSC hull is shown in Figure 2 and the body plan is shown in Figure 3. The detailed panel information is given in the file *alsc.panel* (Appendix A).

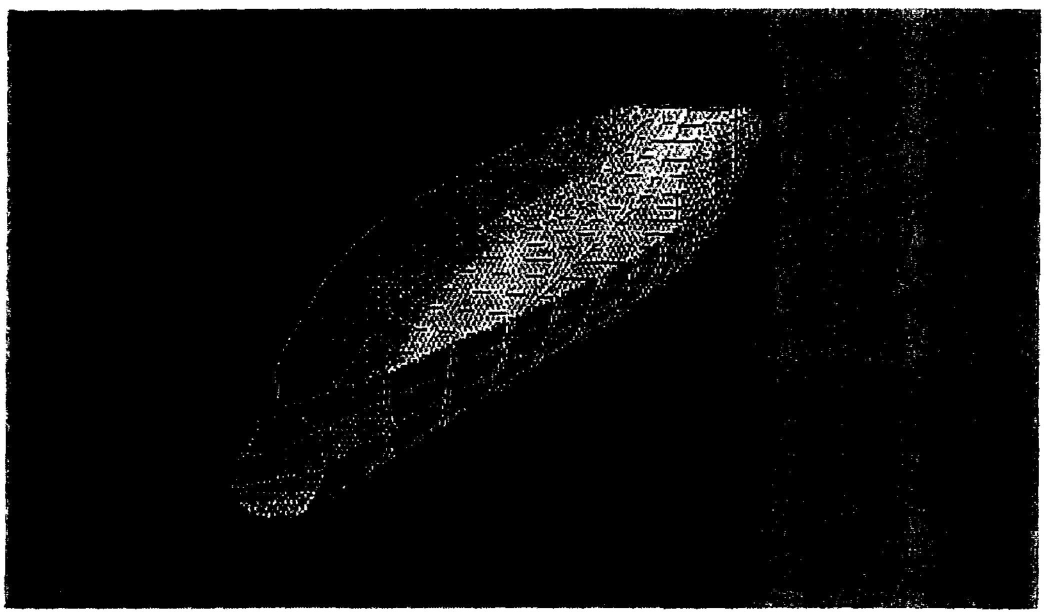


Figure 2: Panelized ALSC Hull

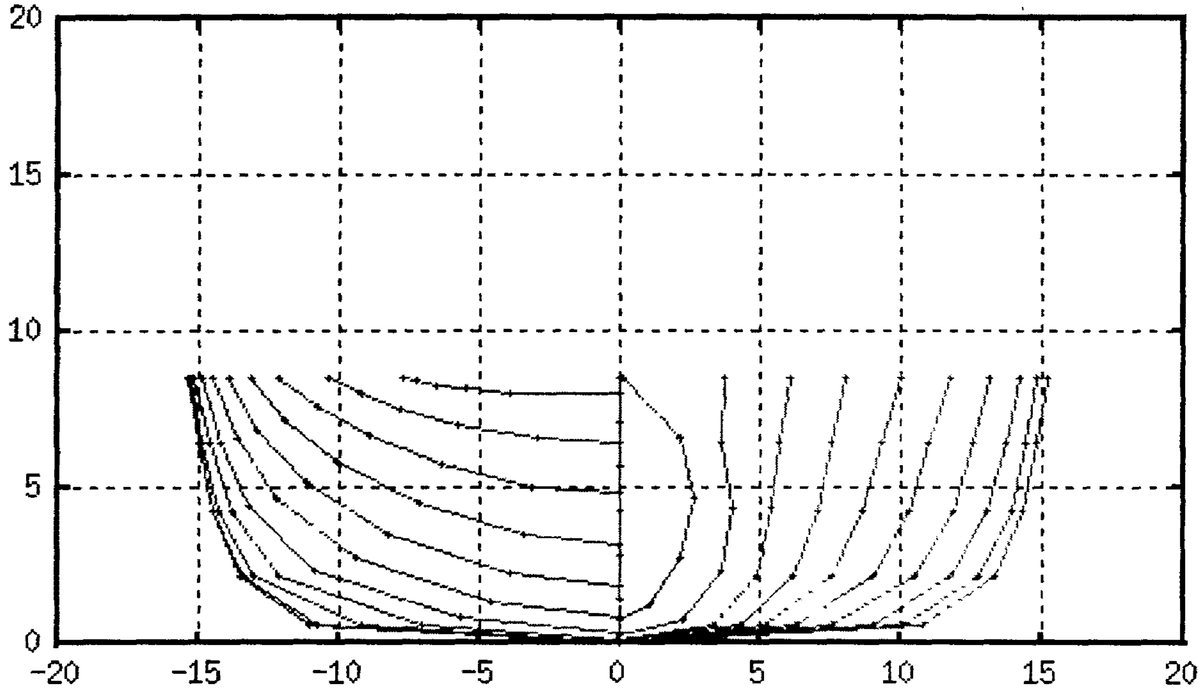


Figure 3: Body Plan of ALSC Hull

5.1.2 SCAN frigate hull: ship-b

The SCAN frigate is panelized with 26 stations and 19 waterlines. The principal dimensions of the SCAN Frigate are as follows:

$L = 122.m$
$B = 14.783m$
$T = 4.5m$
$Trim = 0.24m$ (by stern)
$D = 4023.7tonnes$
$Cb = 0.484$
$Xg = 3.284m$ (forward midships)
$Yg = 0.0m$
$Zg = 2.049m$ (relative to the calm waterline)
$Rxx = 4.921m$
$Ryy = 30.5m$
$Rzz = 30.5m$

The SCAN frigate hull is also panelized using *PANELGEN*. The difference between the SCAN frigate and the ALSC in panelization is that a trim had to be considered for the SCAN frigate. The panelized SCAN frigate hull is shown in Figure 4 and the body plan is shown in Figure 5. Detailed panel information is given in the file *scan.panel* (Appendix B).

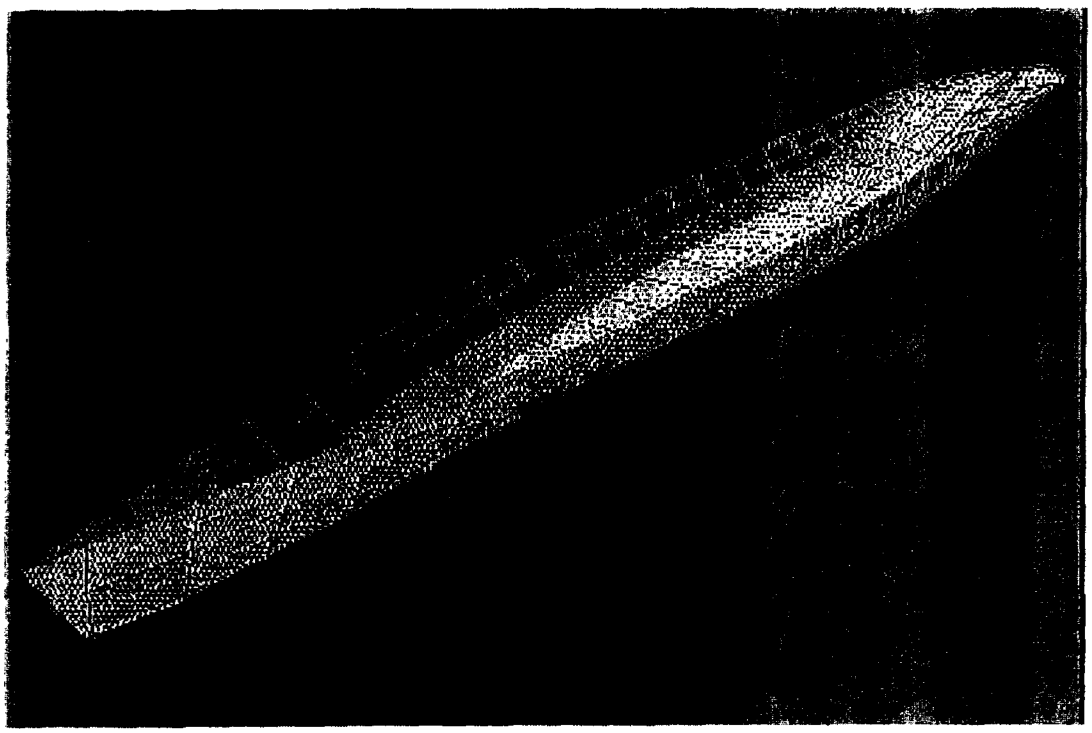


Figure 4: Panelized SCAN Frigate Hull

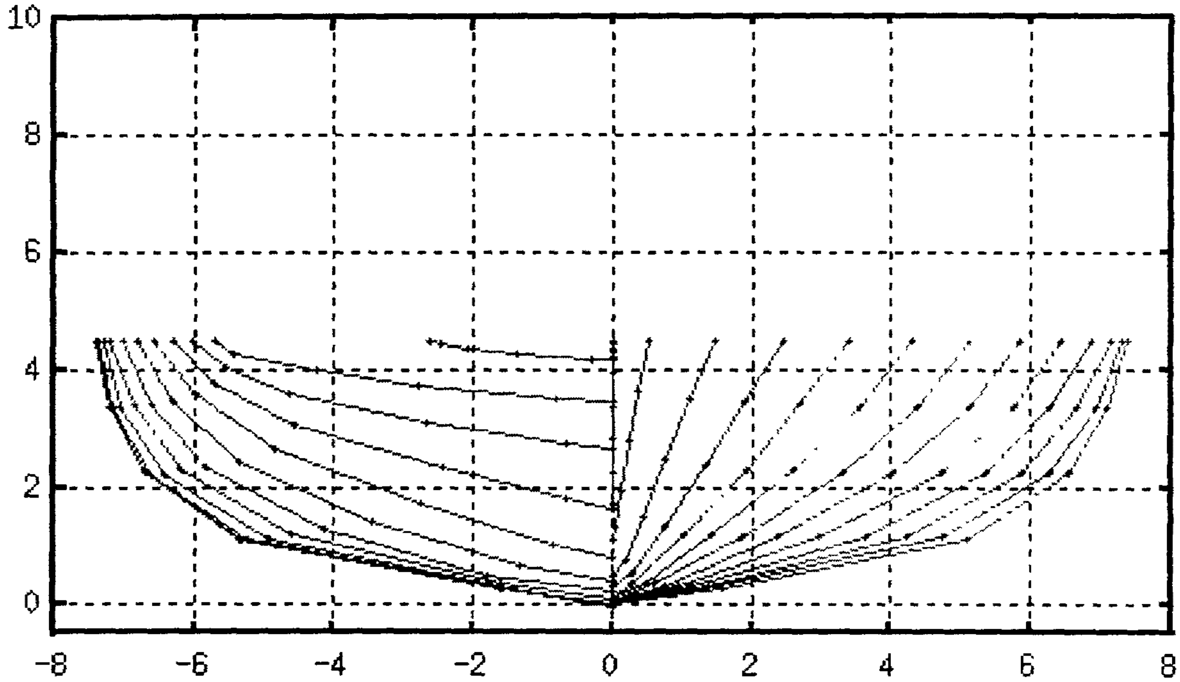


Figure 5: Body Plan of the SCAN Frigate Hull

5.2 Calculation of hull parameters for viscous damping.

The input file *vdamp-a.in* for the ALSC and *vdamp-b.in* for the SCAN frigate provide all the necessary data to compute the following viscous roll damping coefficients:

- The bilge keel viscous roll damping coefficients.
- The eddy-making viscous roll damping coefficients.
- The frictional viscous roll damping coefficients.
- The appendage (other than bilge keel) viscous roll damping coefficients.
- The lifting viscous roll damping coefficient of rudder and skeg.

or the sum of any combinations of the above components.

The Bilge Keel Data:

	ALSC	SCAN frigate
stations spanned:	8.0-13.0	8.3-12.8
bilge keel breadth:	0.5 m	0.8 m
bilge keel breadth-length ratio:	0.0111	0.0262

Sectional Parameters:

We obtained the sectional parameters of the ALSC and the SCAN frigate according to the User's Guide for *SHIPINT*.

Rudder and Deadwood Parameters:

The frigate has a single rudder and the ALSC has two podded propulsion units.

	ALSC	SCAN frigate
skeg span :	NONE	2.5 m
vertical distance of C.G. above waterline :	3.925 m	2.055m
rudder span:	NONE	5.3 m
skeg angular parameter:	NONE	1.02 rad
rudder area of single side:	NONE	25.97 m^2

Parameters of Appendages Other Than Bilge Keel:

The ALSC includes 2 vertical foils of elliptical cross-section to model the podded propulsion units. The dimension of these foils are based on preliminary estimates for likely propulsion units. The SCAN Frigate includes 4 pairs of propeller shaft brackets and a sonar dome.

The detailed parameters are as follows:

total number of appendages: ALSC: 2 SCAN frigate: 9

normal force coefficient for a flat plate inclined at a large angle to flow:
ALSC: 1.17 SCAN frigate: 1.17

The appendage parameters:

For ALSC: (append No)	1	2
y at root of appendage(m):	9	-9.0
z at root of appendage(m):	8.3	8.3
appendage dihedral angle(deg.):	90.0	-90.0
end chord of appendage(m):	5.0	5.0
root chord of appendage (m):	5.0	5.0
span of appendage(m):	5.4	5.4

For SCAN frigate: (append No.)	1	2	3	4	5	6	7	8	9
y at root of appendage(m):	3.5	-3.5	1.9	-1.9	4.1	-4.1	1.0	-1.0	0.0
z at root of appendage(m):	2.9	2.9	2.3	2.3	3.6	3.6	2.9	2.9	4.5
appendage dihedral angle(deg):	97.	-97	47	-47	104	-104	48	-48	90
end chord of appendage(m):	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	4.95
root chord of appendage(m)	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	4.95
span of appendage(m):	2.0	2.0	2.0	2.0	3.3	3.3	3.4	3.4	1.16

All of the above information is included in the input files *vdamp-a.in* (for the ALSC) in Appendix C, and *vdamp-b.in* (for the SCAN frigate) in Appendix D.

5.3 Computed Results

The computed results for the ALSC and the SCAN frigate interactions are organized according to the run set number of the model test matrix.

The computed results are:

For the ALSC:

- non-dimensional measurement surge force amplitude $F_1/\rho g \zeta_a L_a B_a$
- non-dimensional measurement sway force amplitude $F_2/\rho g \zeta_a L_a B_a$
- non-dimensional measurement heave force amplitude $F_3/\rho g \zeta_a L_a B_a$
- non-dimensional measurement roll force amplitude $M_4/\rho g \zeta_a L_a^2 B_a$
- non-dimensional measurement pitch force amplitude $M_5/\rho g \zeta_a L_a^2 B_a$
- non-dimensional measurement yaw force amplitude $M_6/\rho g \zeta_a L_a^2 B_a$
- non-dimensional surge motion amplitude ξ_1/ζ_a
- non-dimensional sway motion amplitude ξ_2/ζ_a
- non-dimensional heave motion amplitude ξ_3/ζ_a
- non-dimensional roll motion amplitude $\xi_4/\zeta_a K$
- non-dimensional pitch motion amplitude $\xi_5/\zeta_a K$
- non-dimensional yaw motion amplitude $\xi_6/\zeta_a K$
- root mean square amplitude of surge displacement D1
- root mean square amplitude of sway displacement D2
- root mean square amplitude of heave displacement D3
- root mean square amplitude of roll displacement D4
- root mean square amplitude of pitch displacement D5
- root mean square amplitude of yaw displacement D6
- root mean square amplitude of surge acceleration A1
- root mean square amplitude of sway acceleration A2
- root mean square amplitude of heave acceleration A3

- root mean square amplitude of roll acceleration A4
- root mean square amplitude of pitch acceleration A5
- root mean square amplitude of yaw acceleration A6

For the SCAN frigate:

- non-dimensional measurement surge force amplitude $F_1/\rho g\zeta_a L_b B_b$
- non-dimensional measurement sway force amplitude $F_2/\rho g\zeta_a L_b B_b$
- non-dimensional measurement heave force amplitude $F_3/\rho g\zeta_a L_b B_b$
- non-dimensional measurement roll force amplitude $M_4/\rho g\zeta_a L_b^2 B_b$
- non-dimensional measurement pitch force amplitude $M_5/\rho g\zeta_a L_b^2 B_b$
- non-dimensional measurement yaw force amplitude $M_6/\rho g\zeta_a L_b^2 B_b$
- non-dimensional surge motion amplitude ξ_1/ζ_a
- non-dimensional sway motion amplitude ξ_2/ζ_a
- non-dimensional heave motion amplitude ξ_3/ζ_a
- non-dimensional roll motion amplitude $\xi_4/\zeta_a K$
- non-dimensional pitch motion amplitude $\xi_5/\zeta_a K$
- non-dimensional yaw motion amplitude $\xi_6/\zeta_a K$
- root mean square amplitude of surge displacement D1
- root mean square amplitude of sway displacement D2
- root mean square amplitude of heave displacement D3
- root mean square amplitude of roll displacement D4
- root mean square amplitude of pitch displacement D5
- root mean square amplitude of yaw displacement D6
- root mean square amplitude of surge acceleration A1
- root mean square amplitude of sway acceleration A2
- root mean square amplitude of heave acceleration A3
- root mean square amplitude of roll acceleration A4
- root mean square amplitude of pitch acceleration A5
- root mean square amplitude of yaw acceleration A6

Where ζ_a is the incident wave amplitude, K is the wave number.

5.3.1 Run set 4-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

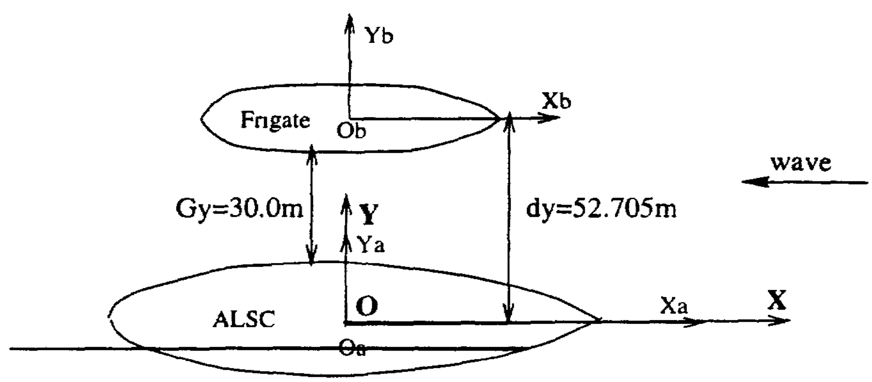
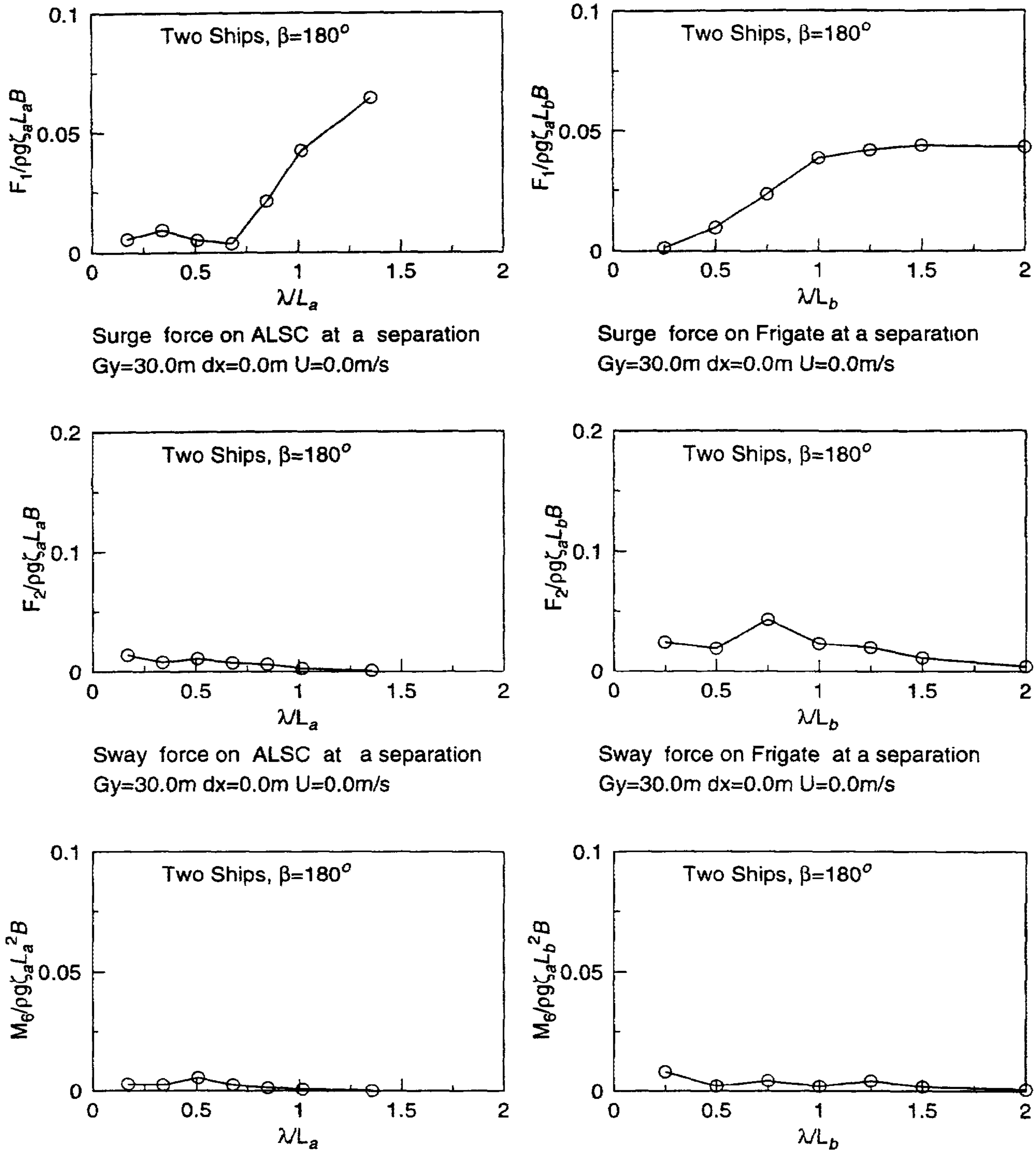


Figure 6: Separation Distance of Two Ships: Gy=30.0m, dx=0.0m



Surge force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s

Surge force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

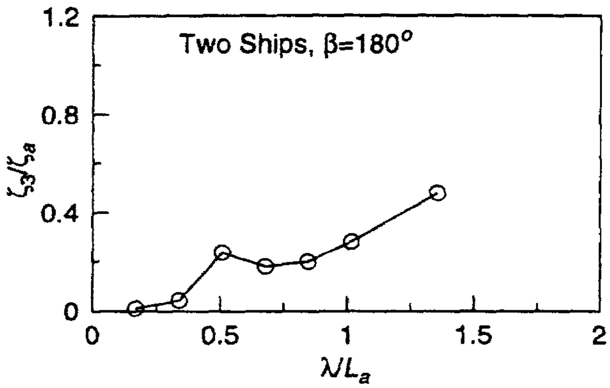
Sway force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s

Sway force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

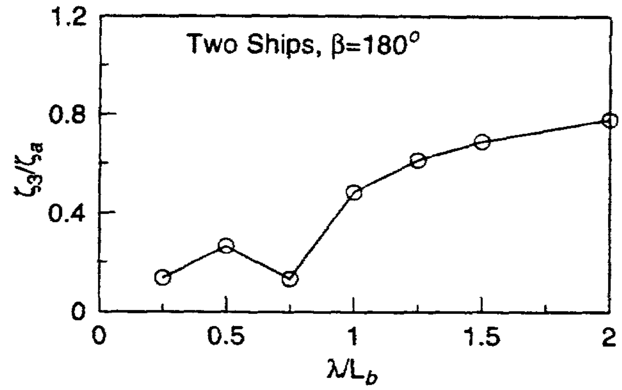
Yaw force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s

Yaw force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

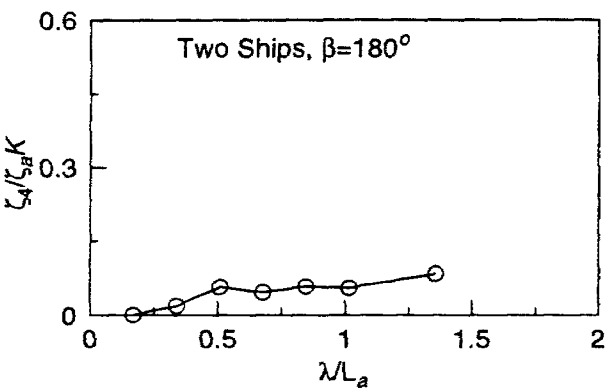
Figure 7: Restraining Forces of Two Ships for Run Set 4-1



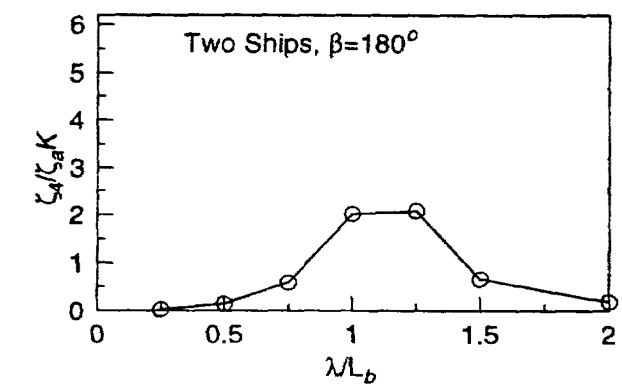
Heave motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



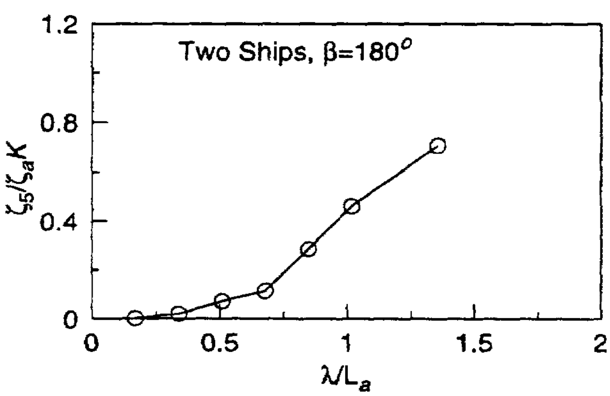
Heave motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



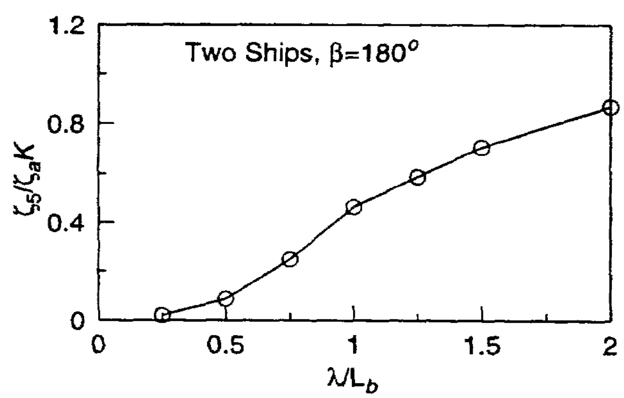
Roll motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

Figure 8: Motion Displacements of Two Ships for Run Set 4-1

5.3.2 Run set 4-2

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 45.0 m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

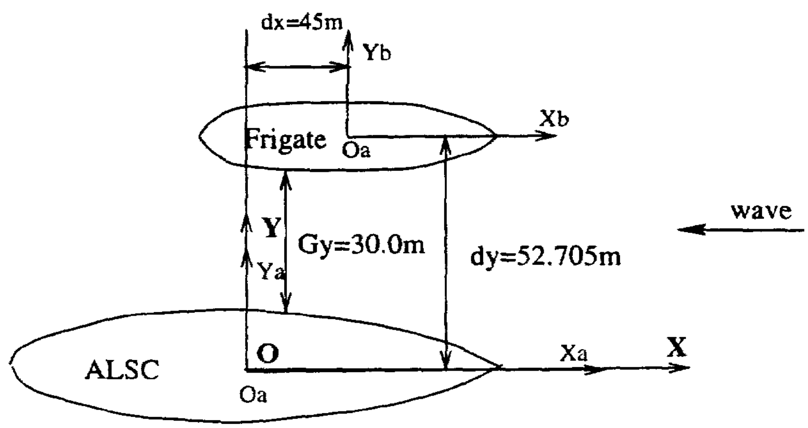
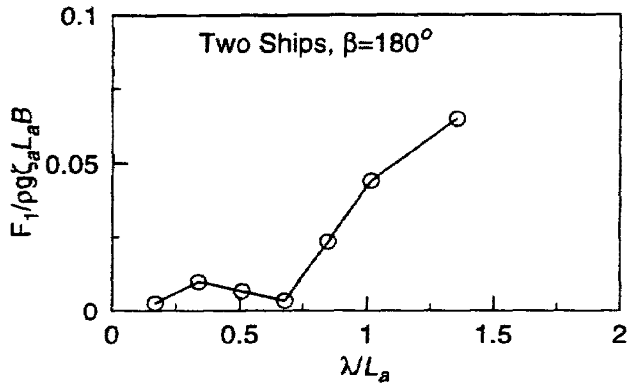
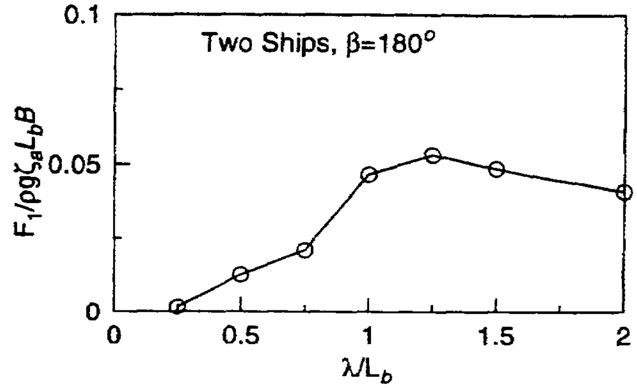


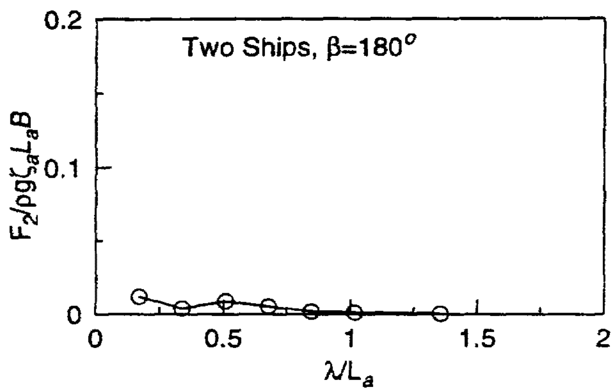
Figure 9: Separation Distance of Two Ships: Gy=30.0m, dx=45.0m



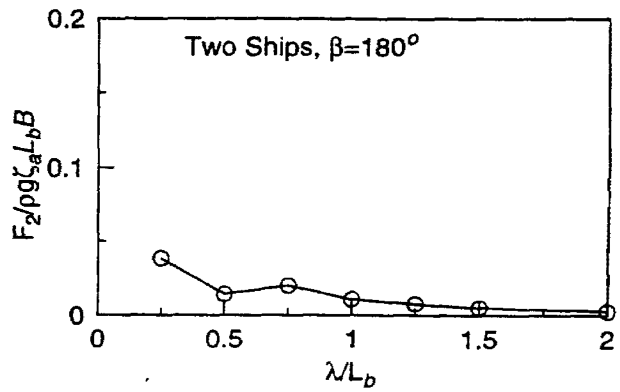
Surge force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



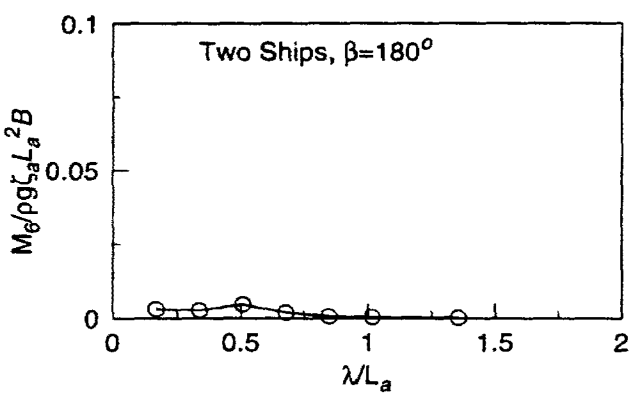
Surge force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



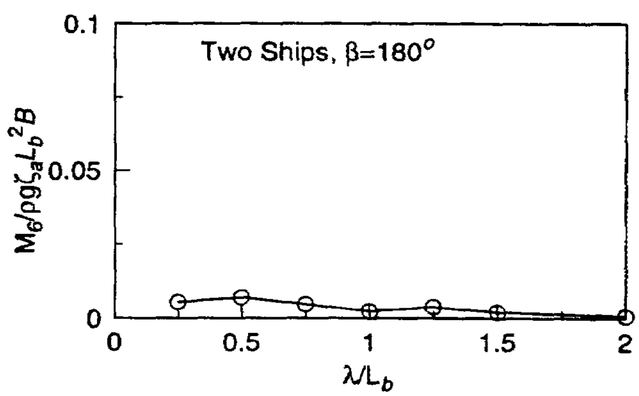
Sway force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

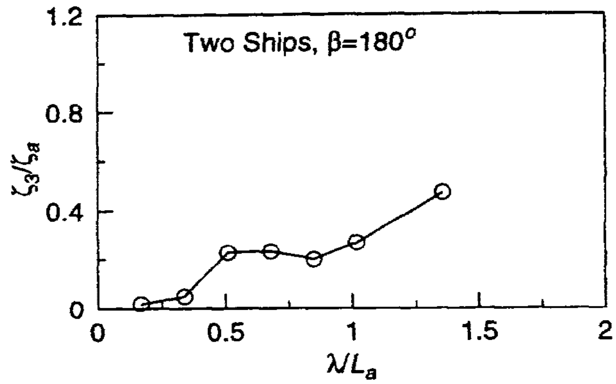


Yaw force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s

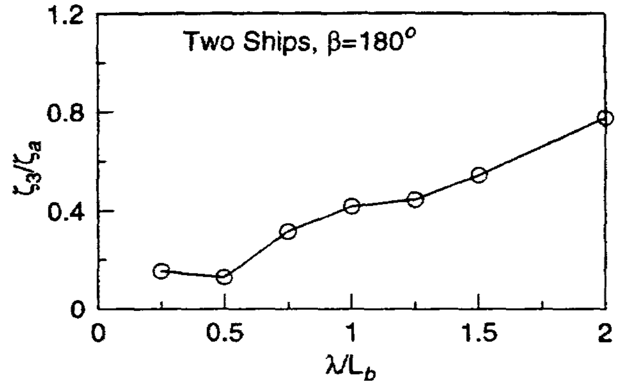


Yaw force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

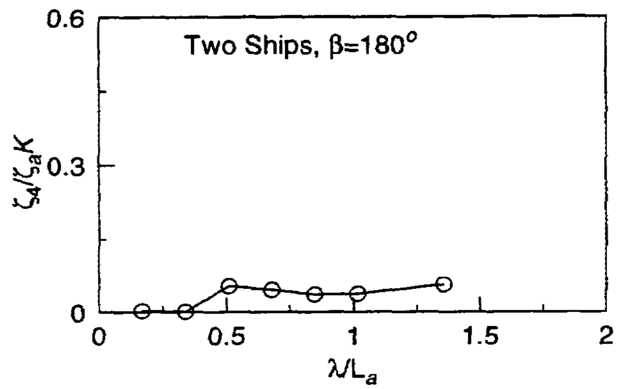
Figure 10: Restraining Forces of Two Ships for Run Set 4-2



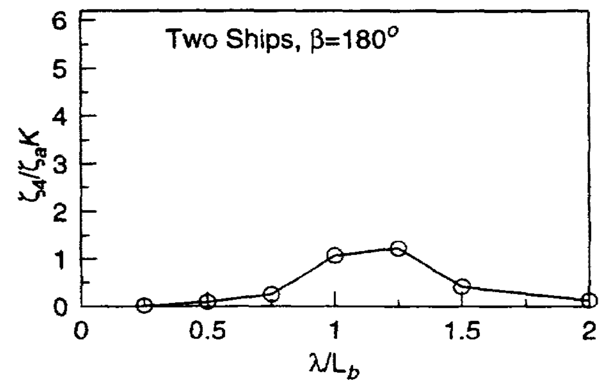
Heave motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



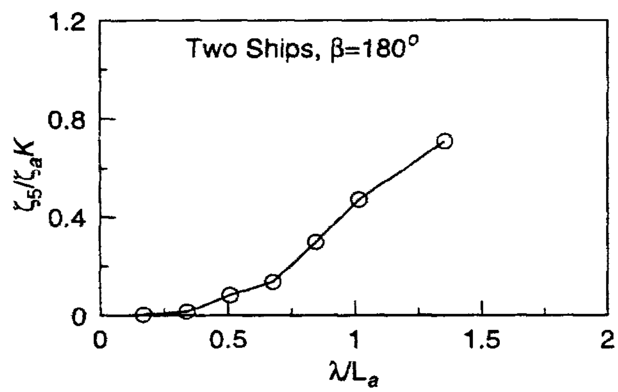
Heave motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



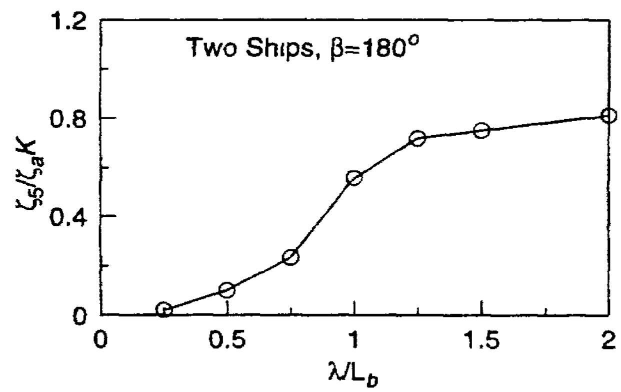
Roll motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

Figure 11: Motion Displacements of Two Ships for Run Set 4-2

5.3.3 Run set 4-3

condition:

Forward speed U=12.0 knots=6.180 m/s
Lateral separation gap $Gy = 30.0$ m
Longitudinal separation distance $dx = 0.0$ m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75. 1.0, 1.25, 1.5$ and 2.0.

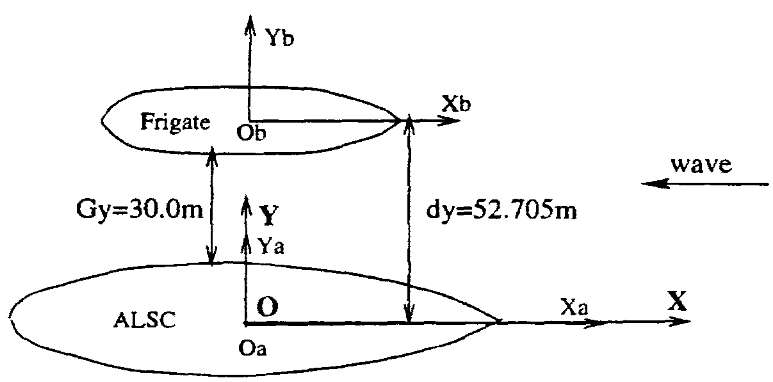
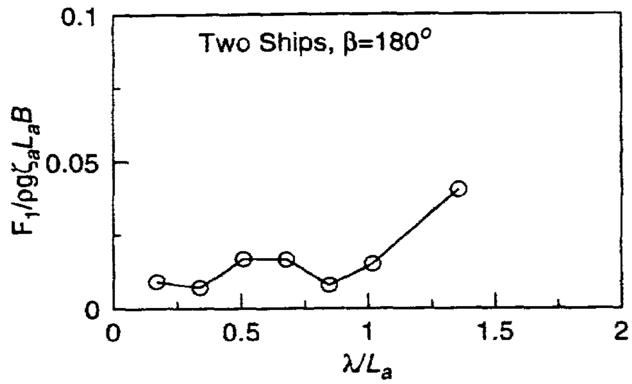
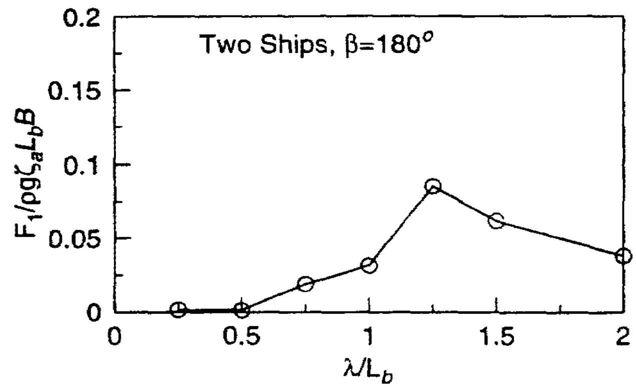


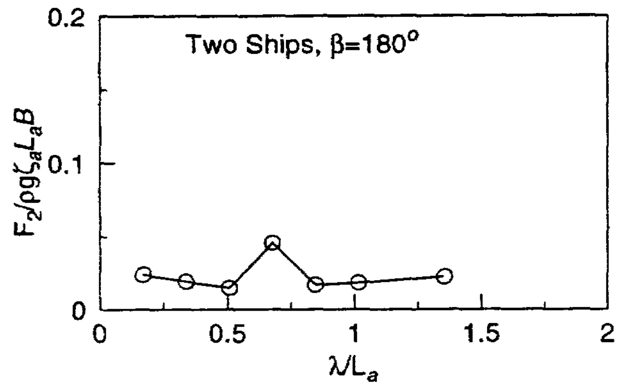
Figure 12: Separation Distance of Two Ships: Gy=30.0m, dx=0.0m



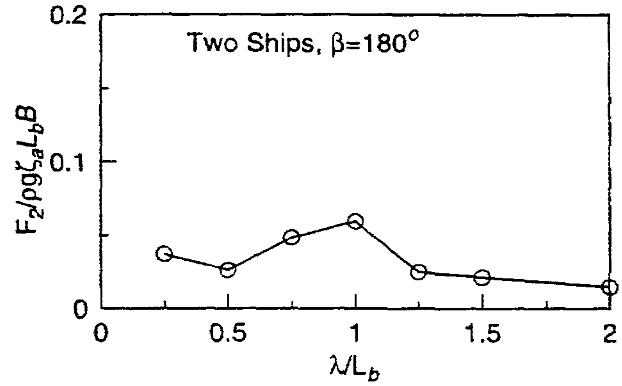
Surge force on ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s



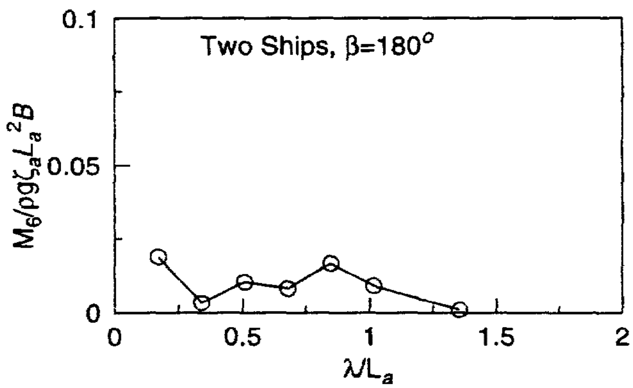
Surge force on Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s



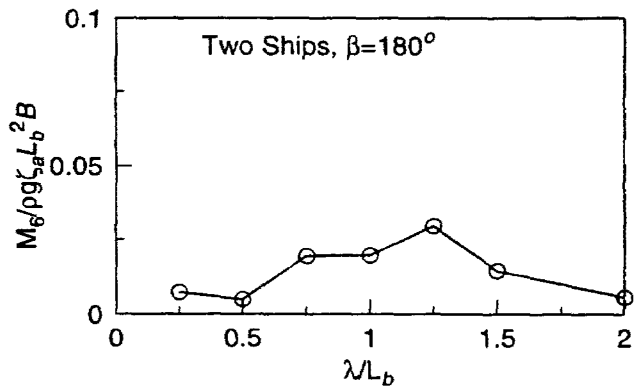
Sway force on ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s



Sway force on Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s

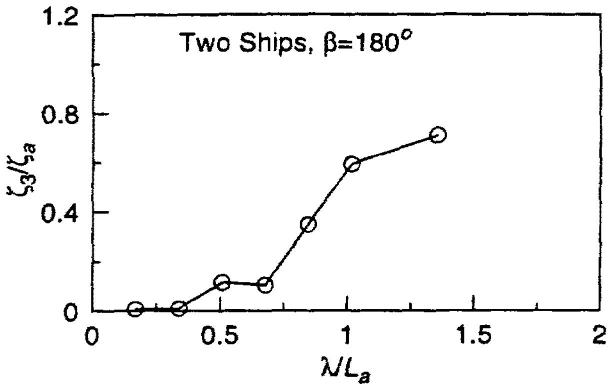


Yaw force on ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s

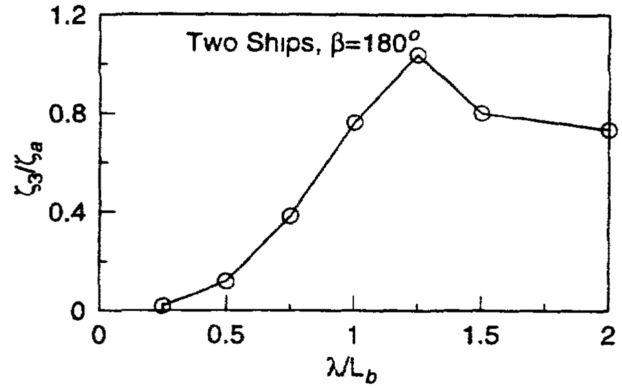


Yaw force on Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s

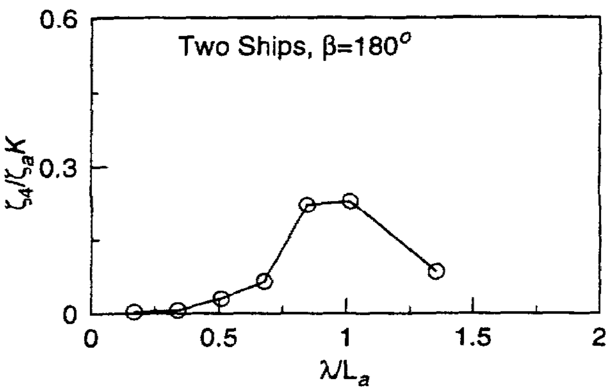
Figure 13: Restraining Forces of Two Ships for Run Set 4-3



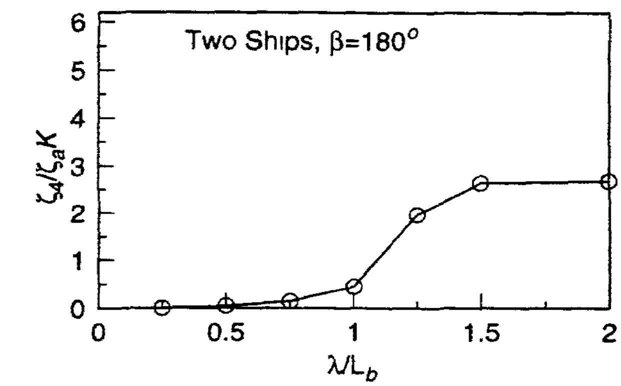
Heave motion of ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s



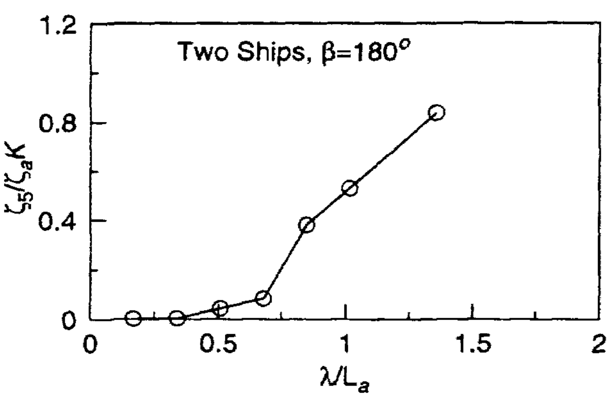
Heave motion of Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s



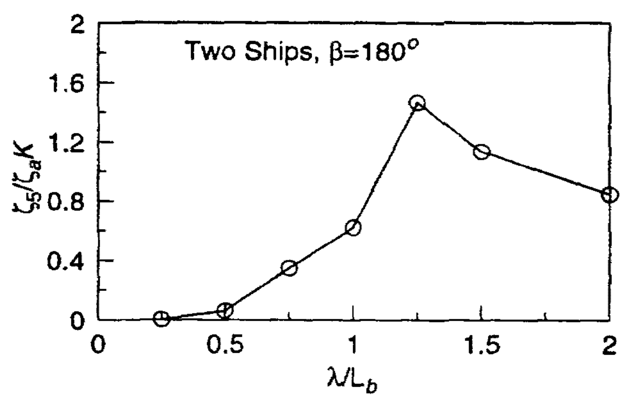
Roll motion of ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=0.0m U=6.18m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=0.0m U=6.18m/s

Figure 14: Motion Displacements of Two Ships for Run Set 4-3

5.3.4 Run set 4-4

condition:

Forward speed U=12.0 knots=6.180 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 45.0 m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

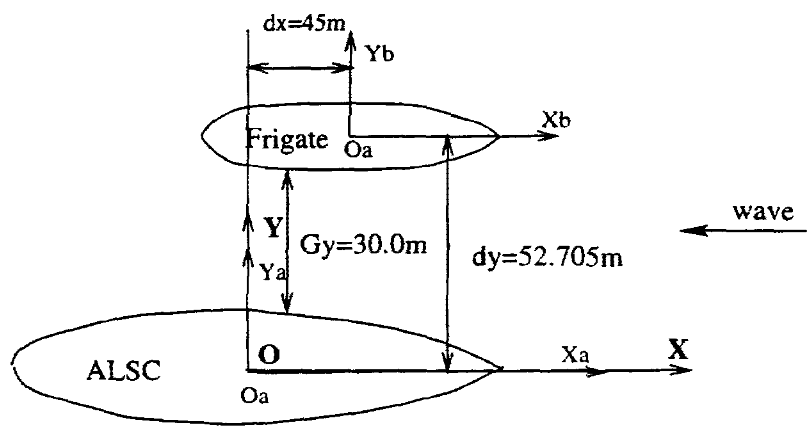
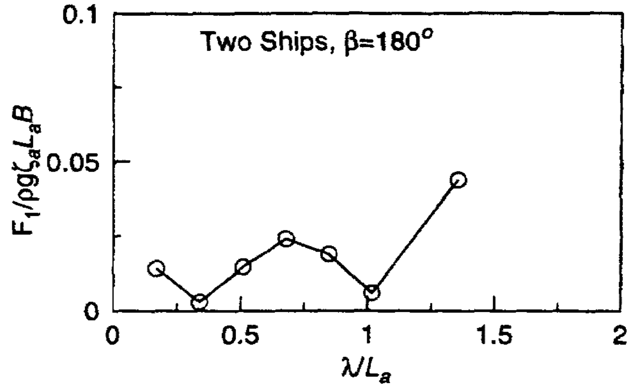
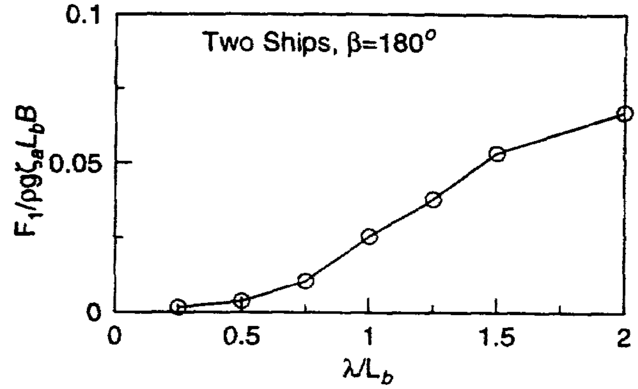


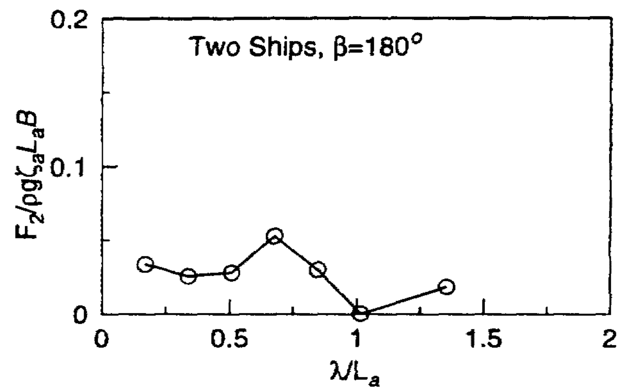
Figure 15: Separation Distance of Two Ships: Gy=30.0m, dx=45.0m



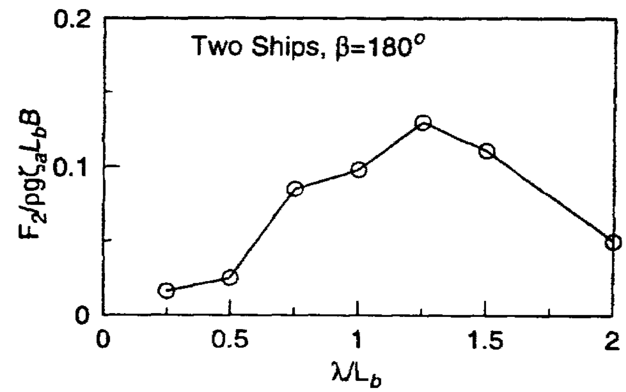
Surge force on ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s



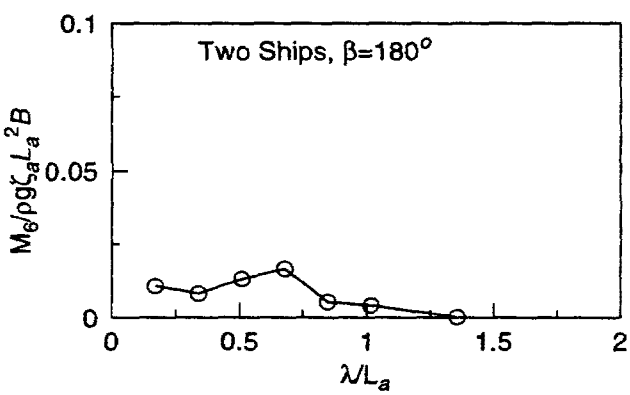
Surge force on Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s



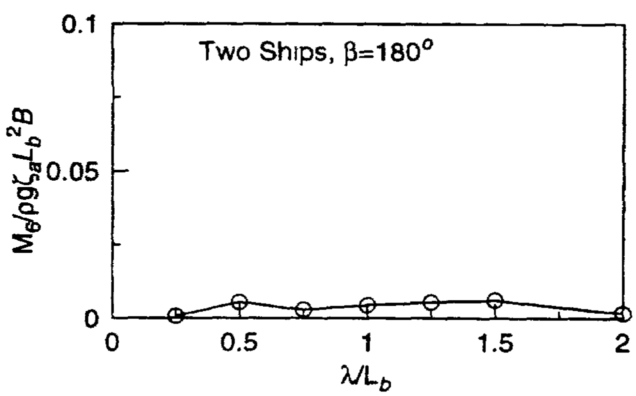
Sway force on ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s



Sway force on Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s

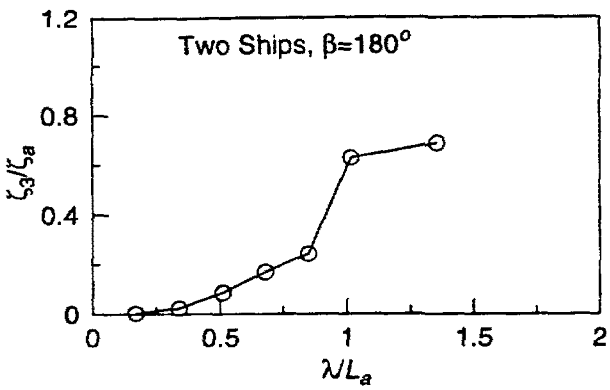


Yaw force on ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s

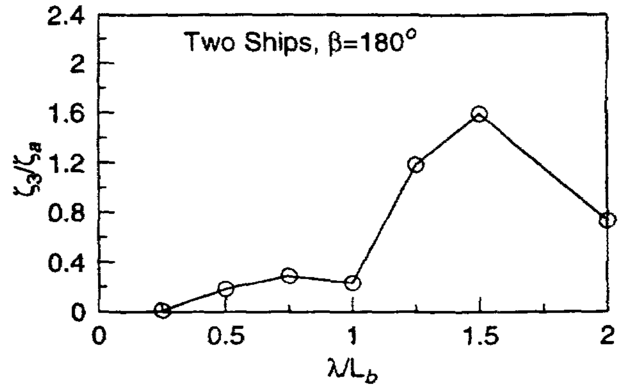


Yaw force on Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s

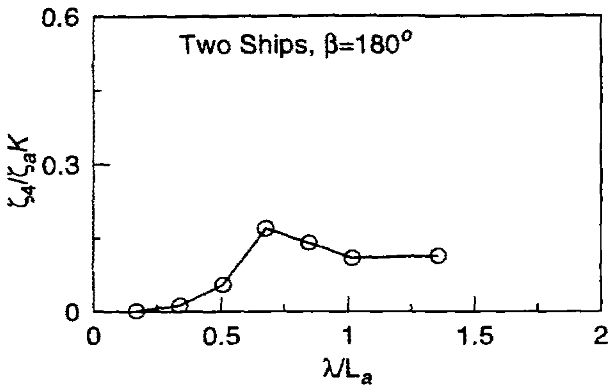
Figure 16: Restraining Forces of Two Ships for Run Set 4-4



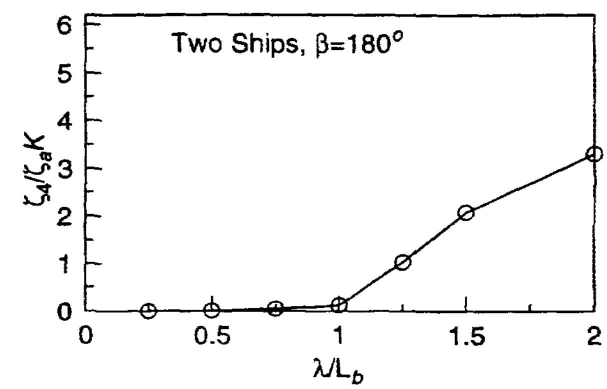
Heave motion of ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s



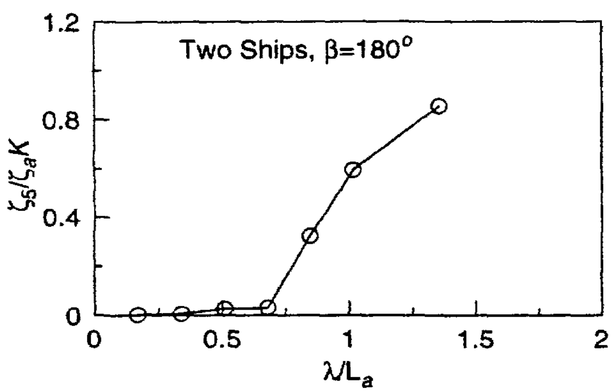
Heave motion of Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s



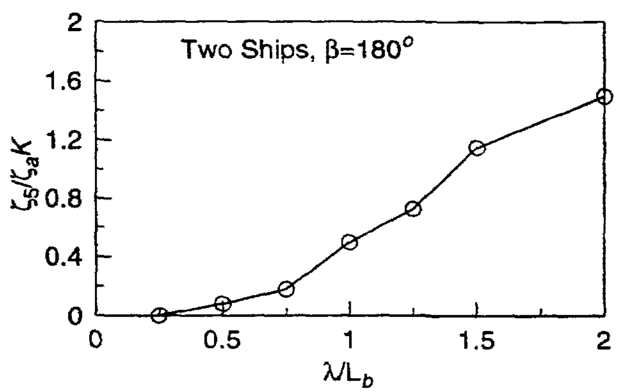
Roll motion of ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=45.0m U=6.18m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=45.0m U=6.18m/s

Figure 17: Motion Displacements of Two Ships for Run Set 4-4

5.3.5 Run set 5-1 and 6-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 2000.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

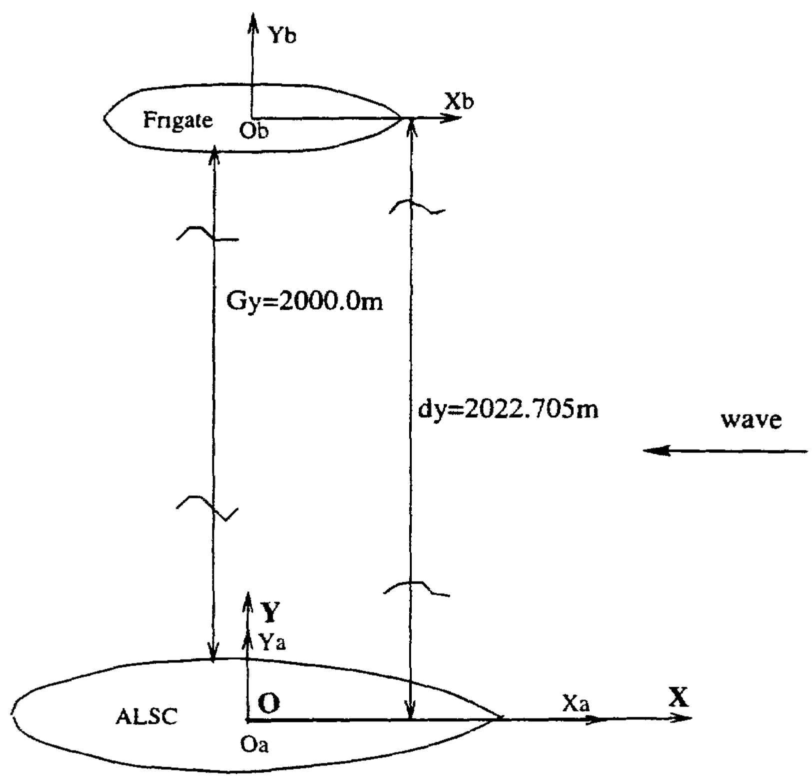
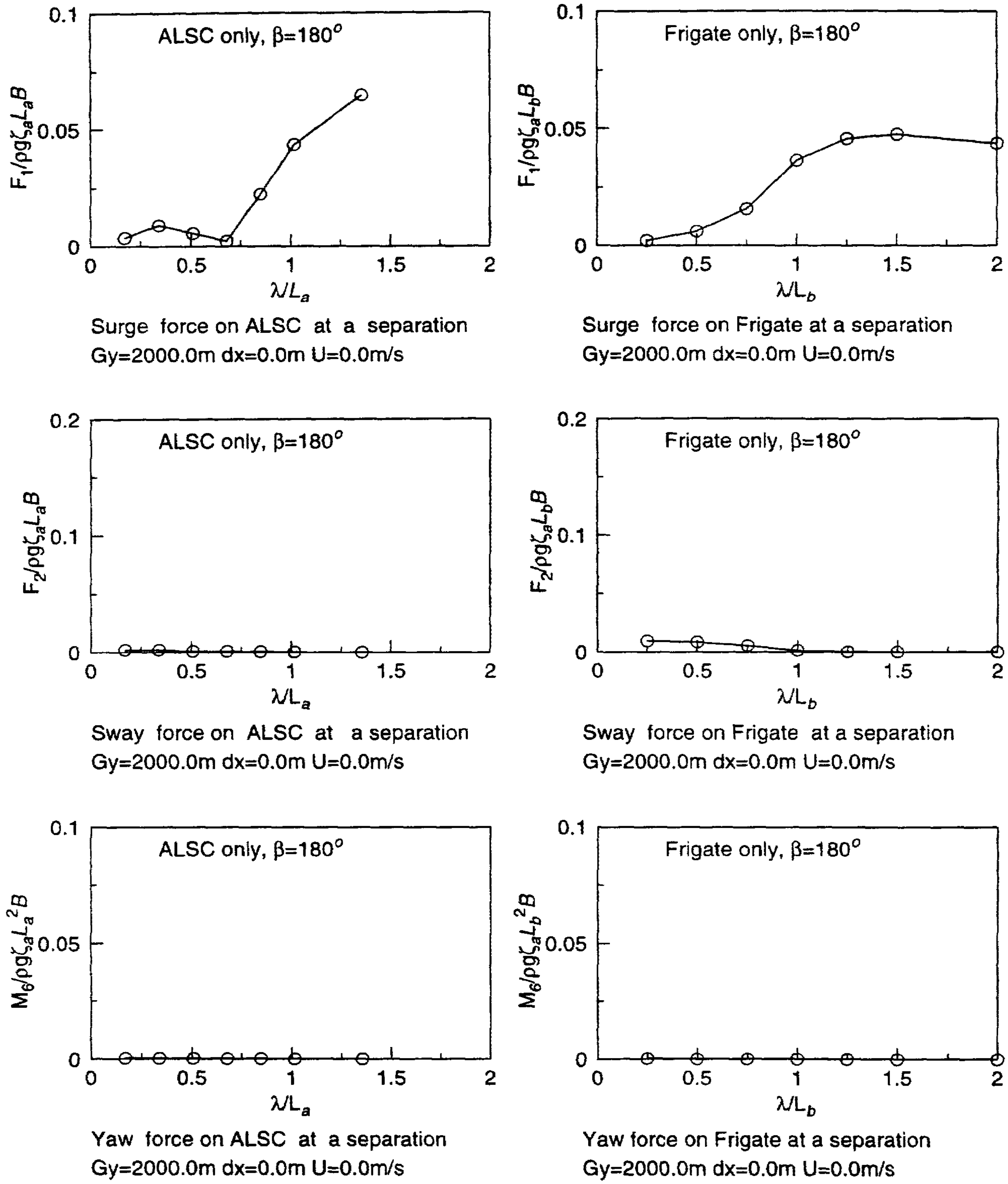


Figure 18: Separation Distance of Two Ships: Gy=2000.0m, dx=0.0m



Surge force on ALSC at a separation Gy=2000.0m dx=0.0m U=0.0m/s

Surge force on Frigate at a separation Gy=2000.0m dx=0.0m U=0.0m/s

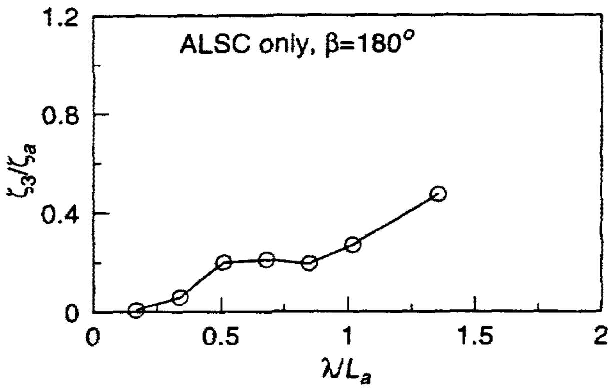
Sway force on ALSC at a separation Gy=2000.0m dx=0.0m U=0.0m/s

Sway force on Frigate at a separation Gy=2000.0m dx=0.0m U=0.0m/s

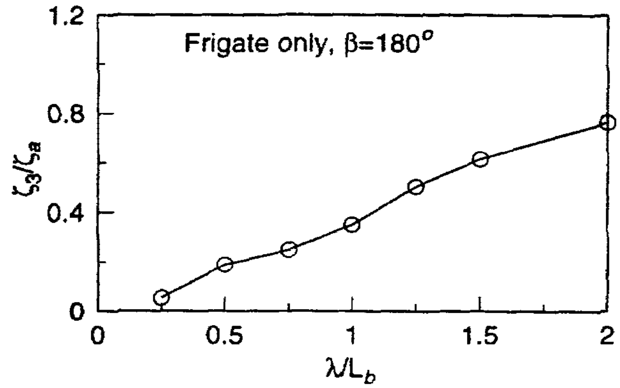
Yaw force on ALSC at a separation Gy=2000.0m dx=0.0m U=0.0m/s

Yaw force on Frigate at a separation Gy=2000.0m dx=0.0m U=0.0m/s

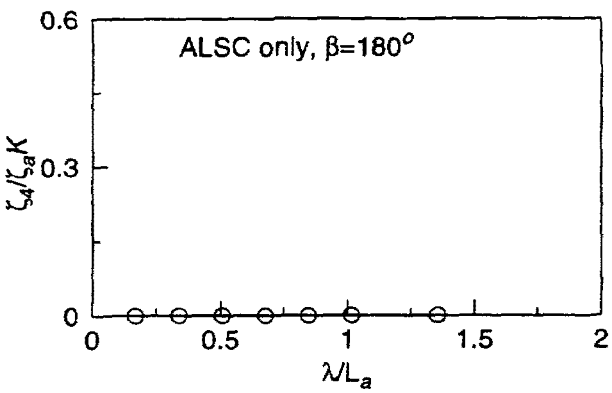
Figure 19: Restraining Forces of Two Ships for Run Set 5-1 and 6-1



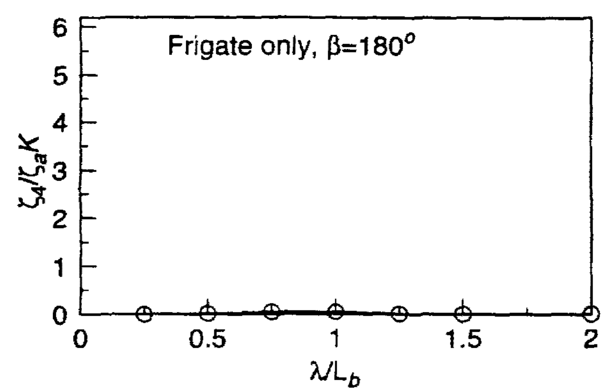
Heave motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



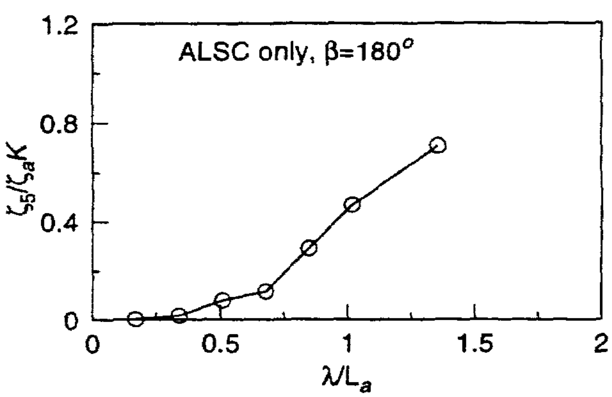
Heave motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



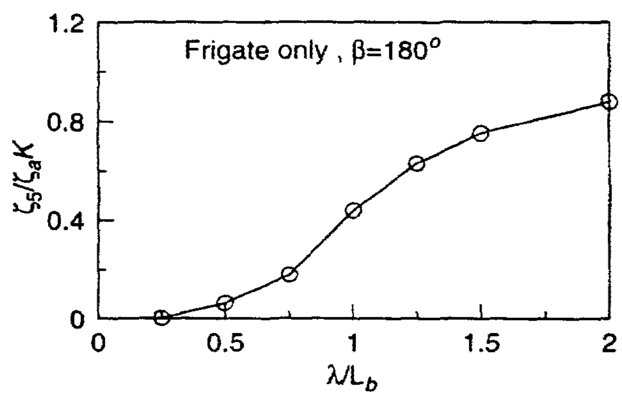
Roll motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

Figure 20: Motion Displacements of Two Ships for Run Set 5-1 and 6-1

5.3.6 Run set 5-2 and 6-2

condition:

Forward speed U=12.0 knots=6.180 m/s
Lateral separation gap Gy = 2000.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 180^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

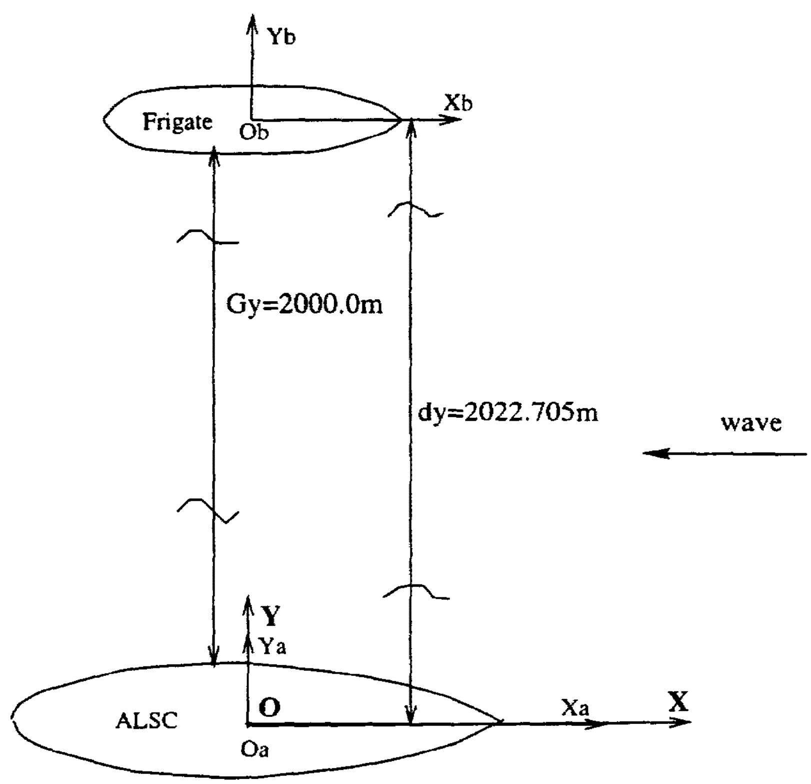
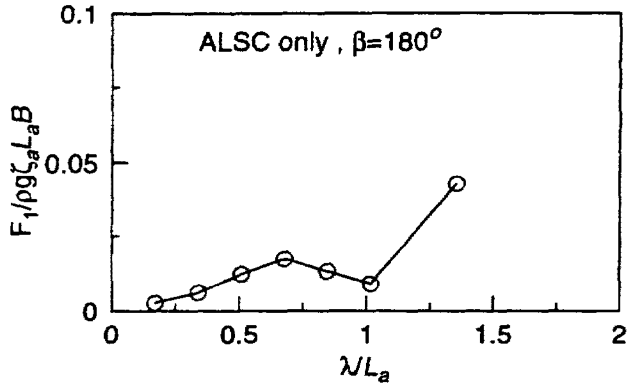
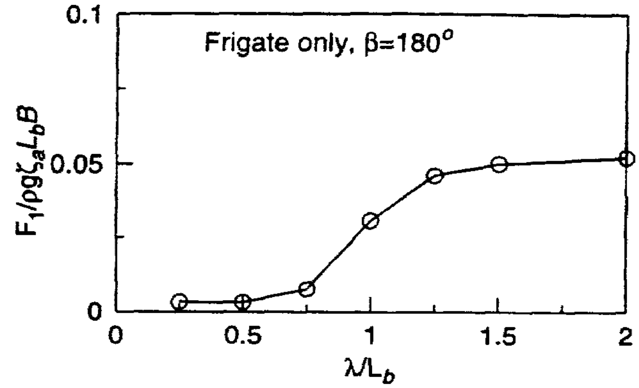


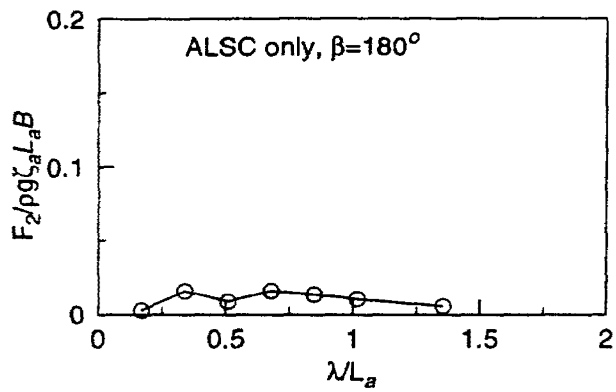
Figure 21: Separation Distance of Two Ships: Gy=2000.0m, dx=0.0m



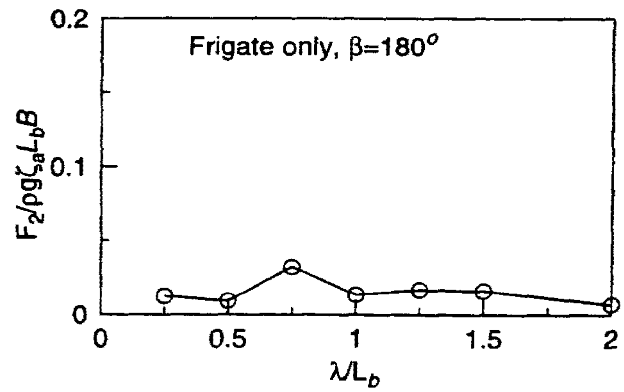
Surge force on ALSC at a separation
Gy=2000.0m dx=0.0m U=6.18m/s



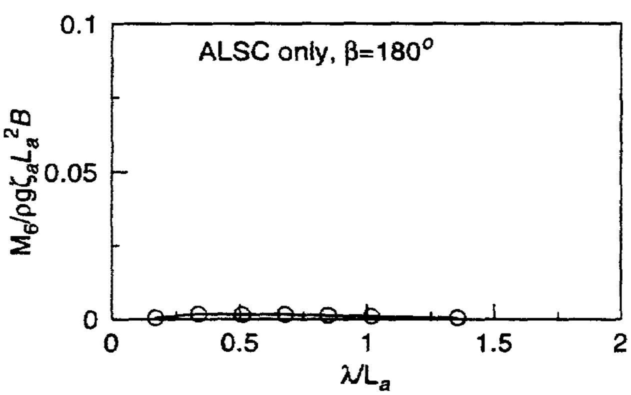
Surge force on Frigate at a separation
Gy=2000.0m dx=0.0m U=6.18m/s



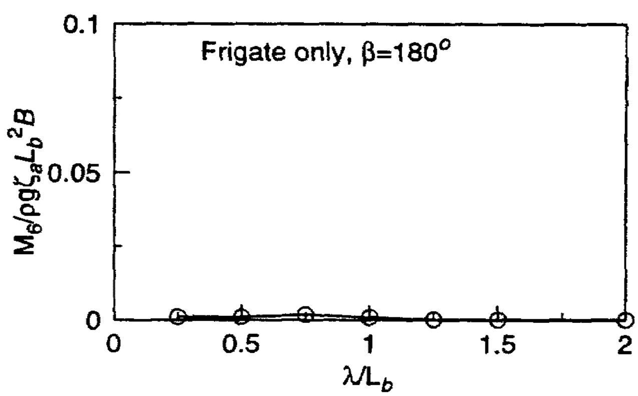
Sway force on ALSC at a separation
Gy=2000.0m dx=0.0m U=6.18m/s



Sway force on Frigate at a separation
Gy=2000.0m dx=0.0m U=6.18m/s

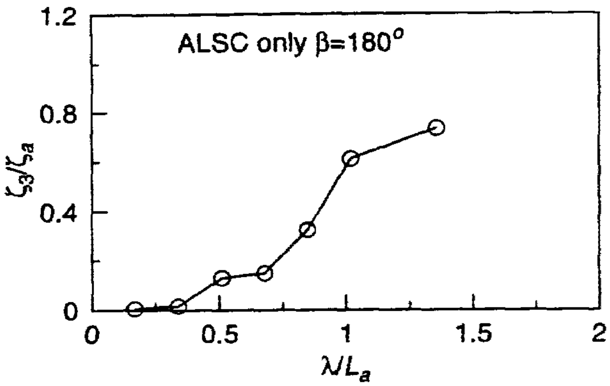


Yaw force on ALSC at a separation
Gy=2000.0m dx=0.0m U=6.18m/s

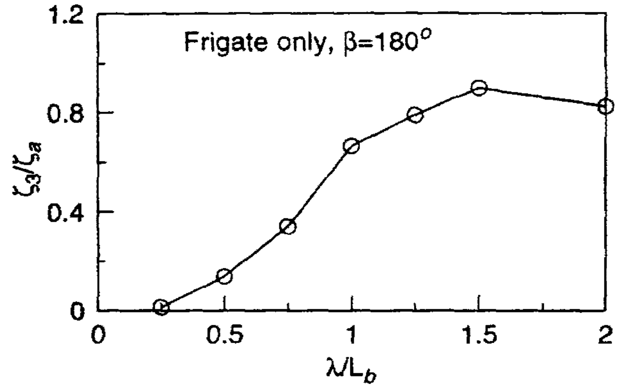


Yaw force on Frigate at a separation
Gy=2000.0m dx=0.0m U=6.18m/s

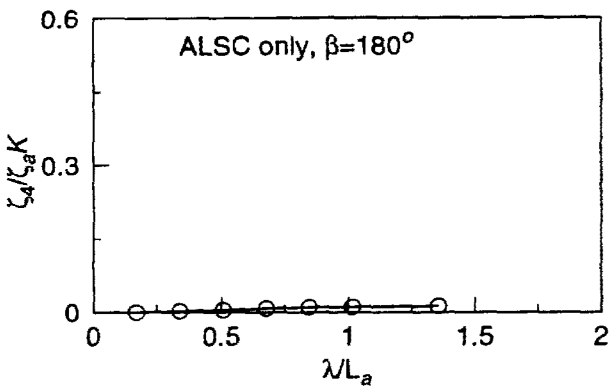
Figure 22: Restraining Forces of Two Ships for Run Set 5-2 and 6-2



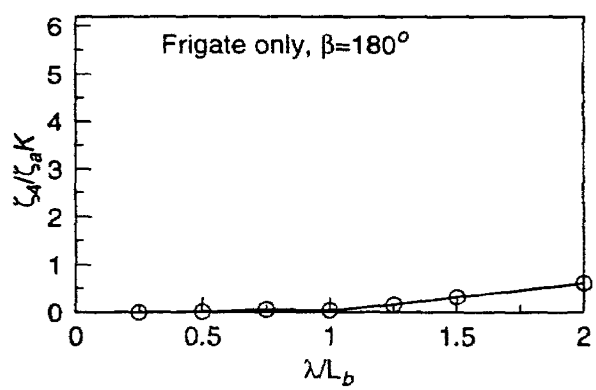
Heave motion of ALSC at a separation Gy=2000.0m dx=0.0m U=6.18m/s



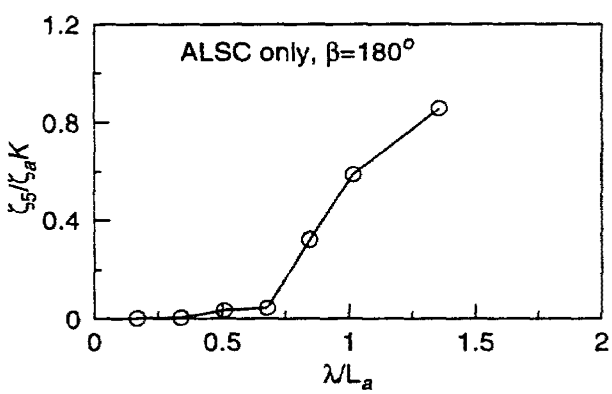
Heave motion of Frigate at a separation Gy=2000.0m dx=0.0m U=6.18m/s



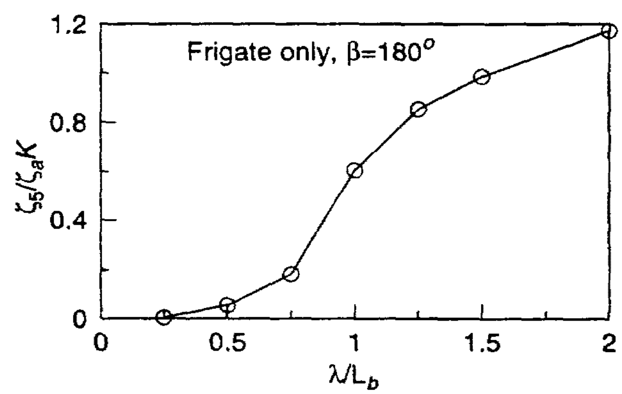
Roll motion of ALSC at a separation Gy=2000.0m dx=0.0m U=6.18m/s



Roll motion of Frigate at a separation Gy=2000.0m dx=0.0m U=6.18m/s



Pitch motion of ALSC at a separation Gy=2000.0m dx=0.0m U=6.18m/s



Pitch motion of Frigate at a separation Gy=2000.0m dx=0.0m U=6.18m/s

Figure 23: Motion Displacements of Two Ships for Run Set 5-2 and 6-2

5.3.7 Run set 7-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 150^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

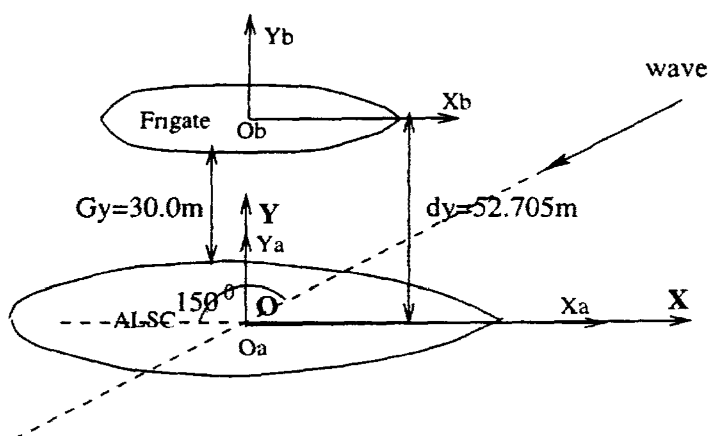
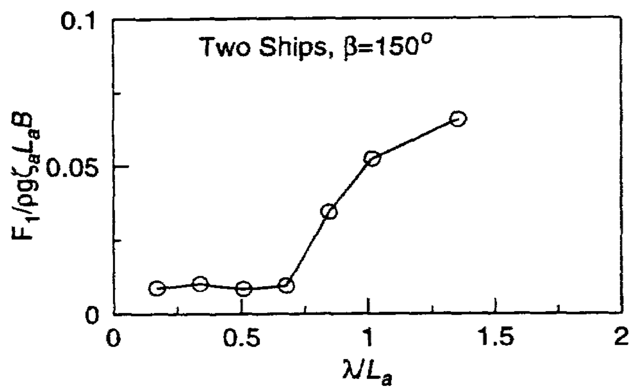
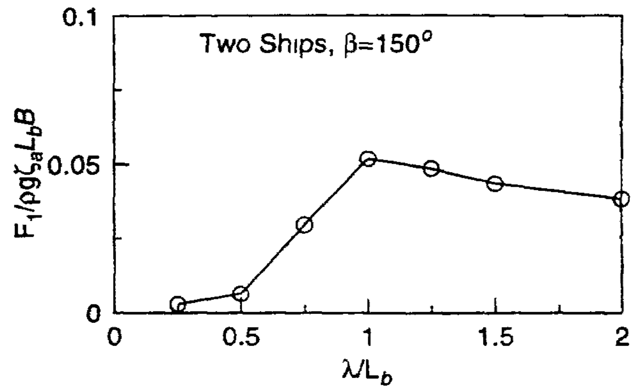


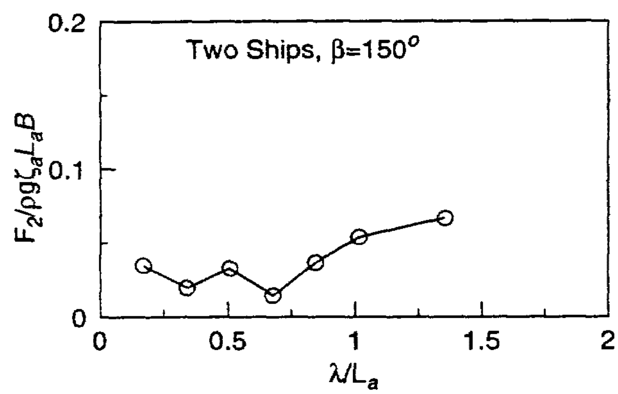
Figure 24: Separation Distance of Two Ships: Gy=30.0m, dx=0.0m



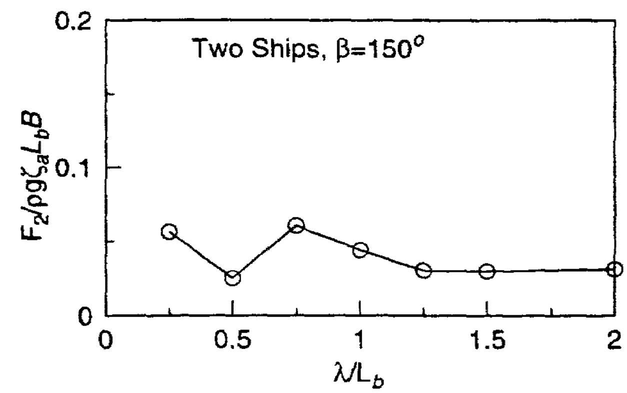
Surge force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



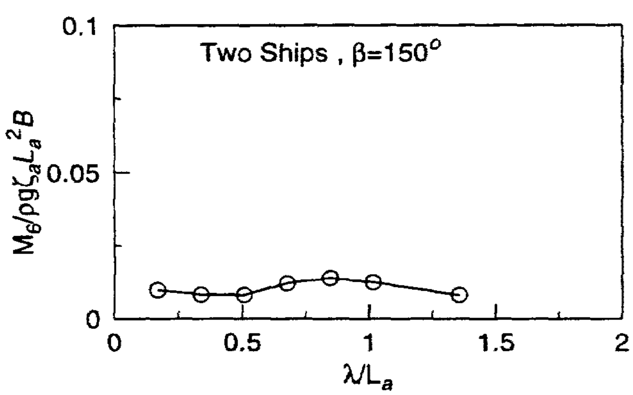
Surge force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



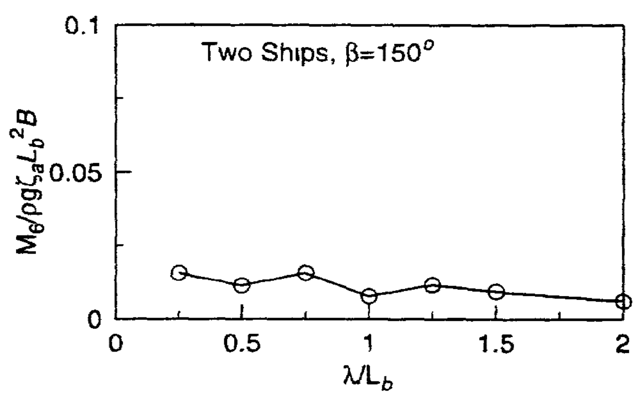
Sway force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

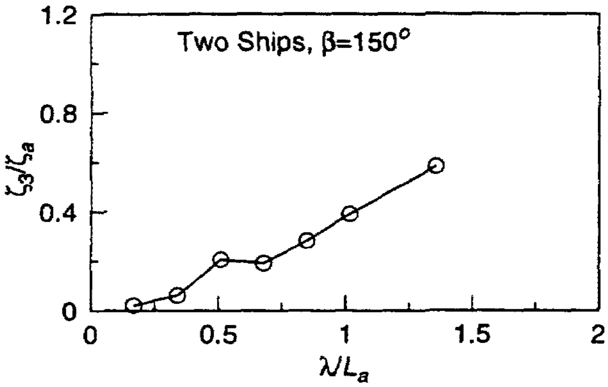


Yaw force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s

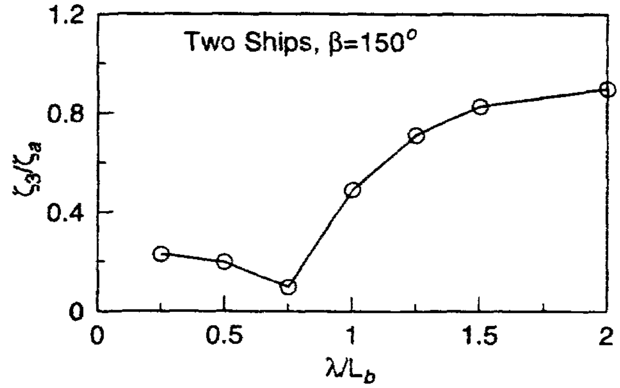


Yaw force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

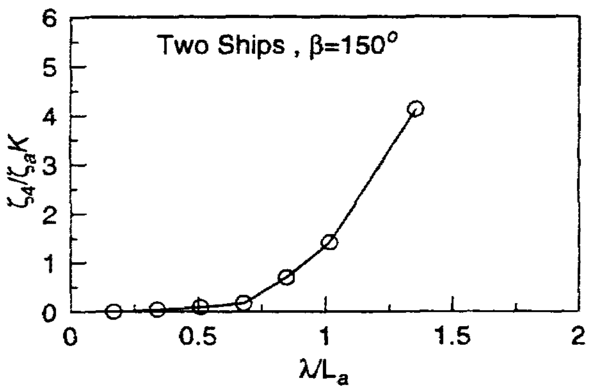
Figure 25: Restraining Forces of Two Ships for Run Set 7-1



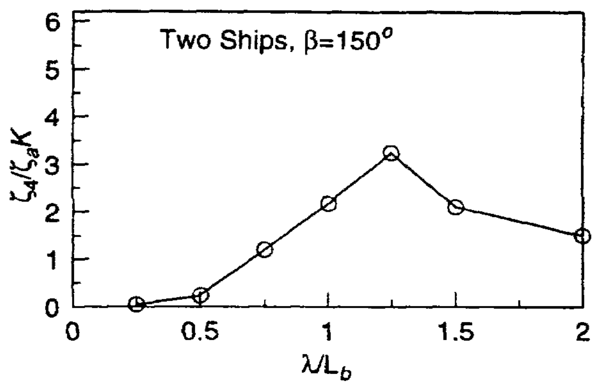
Heave motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



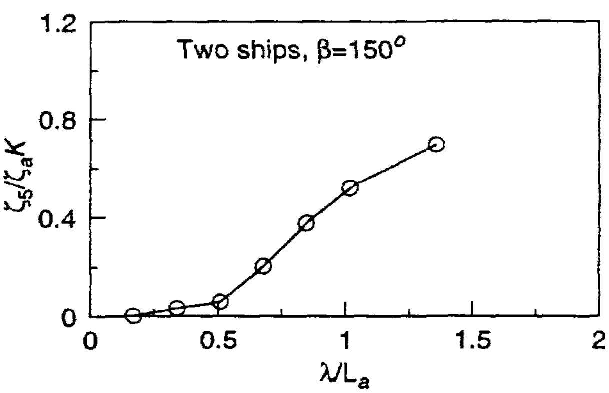
Heave motion of Frigate At a separation
Gy=30.0m dx=0.0m U=0.0m/s



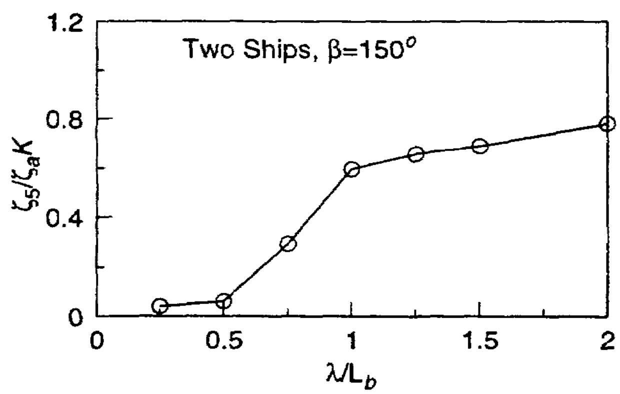
Roll motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate At a separation
Gy=30.0m dx=0.0m U=0.0m/s

Figure 26: Motion Displacements of Two Ships for Run Set 7-1

5.3.8 Run set 7-2

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 45.0 m
Wave heading angle = 150^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

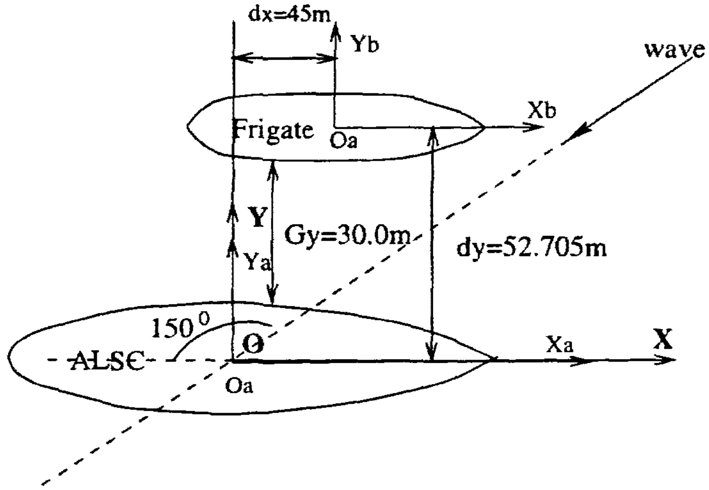
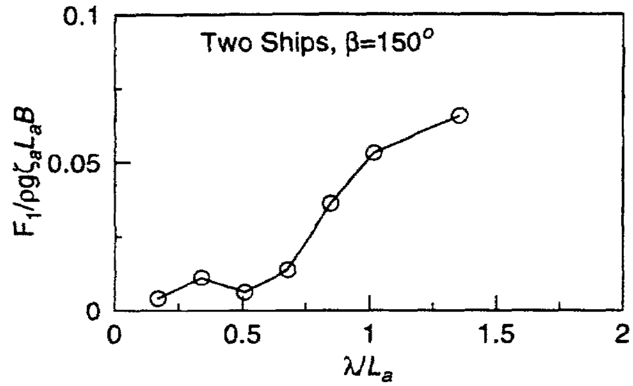
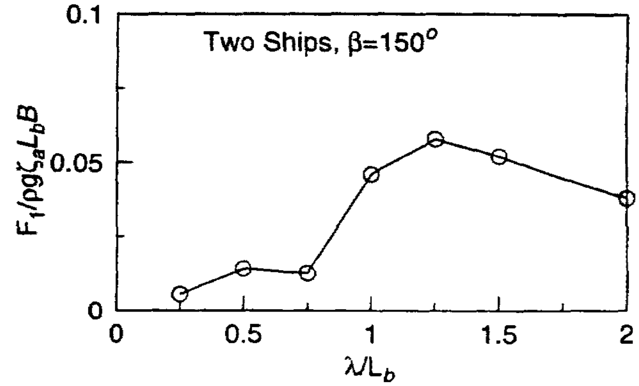


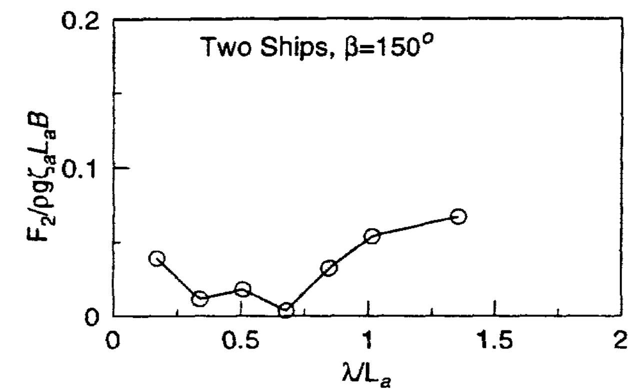
Figure 27: Separation Distance of Two Ships: Gy=30.0m, dx=45.0m



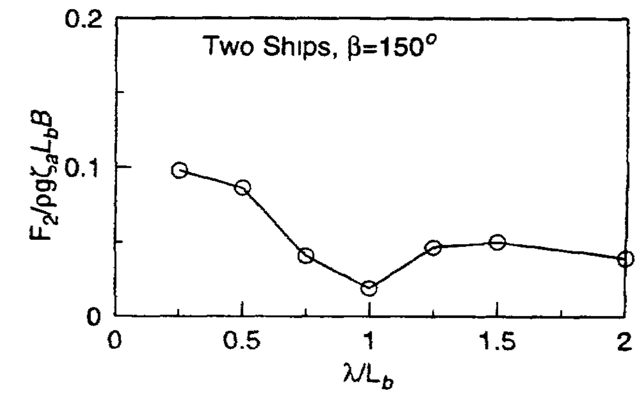
Surge force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



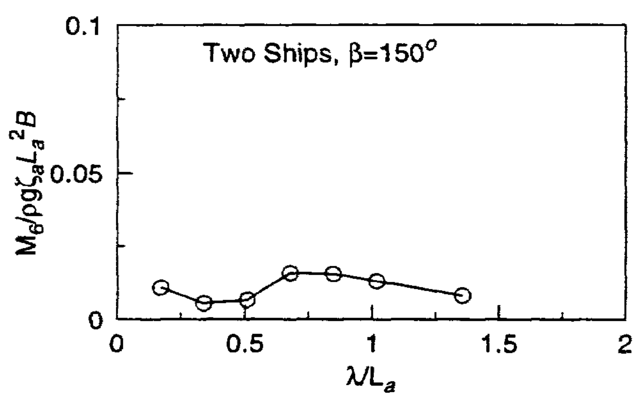
Surge force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



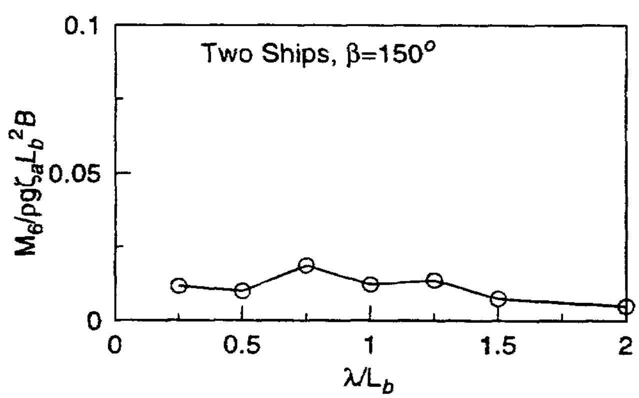
Sway force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

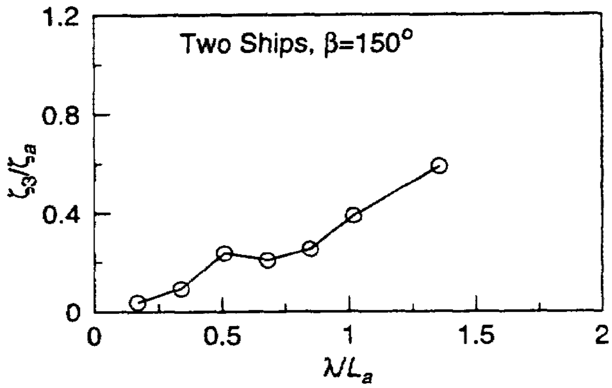


Yaw force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s

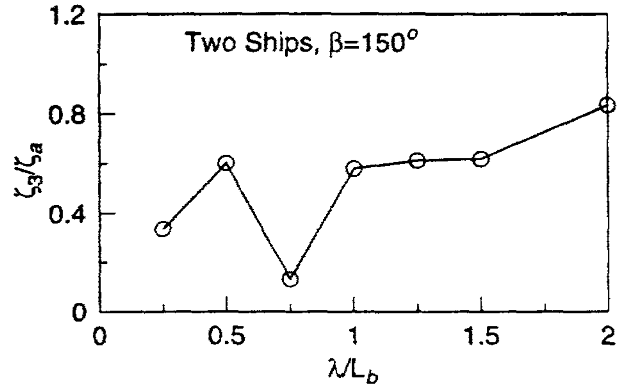


Yaw force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

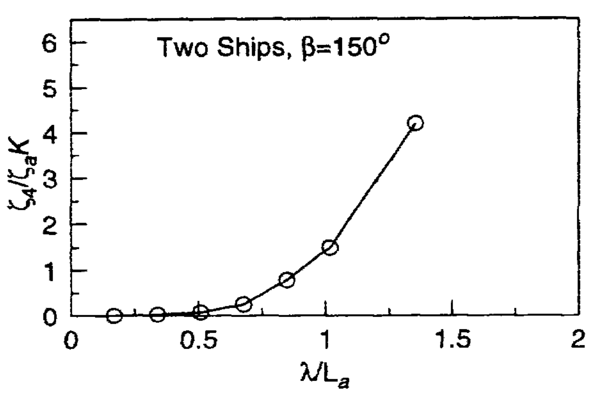
Figure 28: Restraining Forces of Two Ships for Run Set 7-2



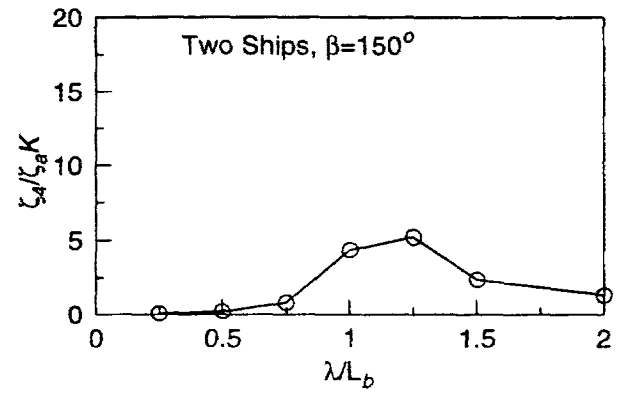
Heave motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



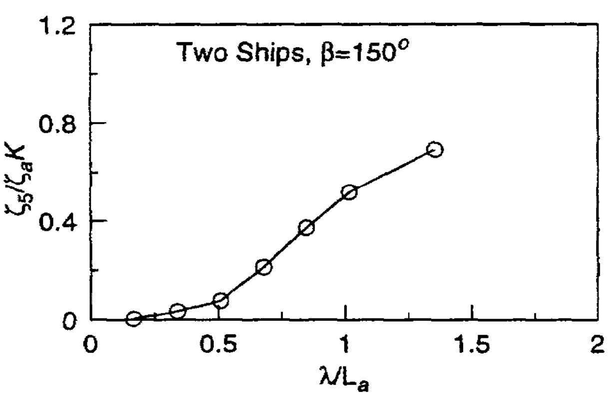
Heave motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



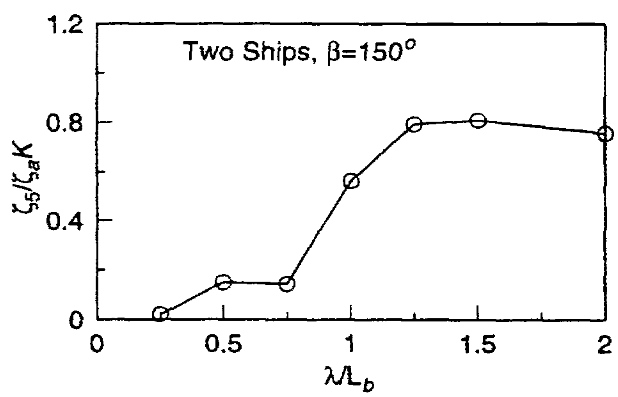
Roll motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

Figure 29: Motion Displacements of Two Ships for Run Set 7-2

5.3.9 Run set 8-1 and 9-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 2000.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 150^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75. 1.0, 1.25, 1.5$ and 2.0.

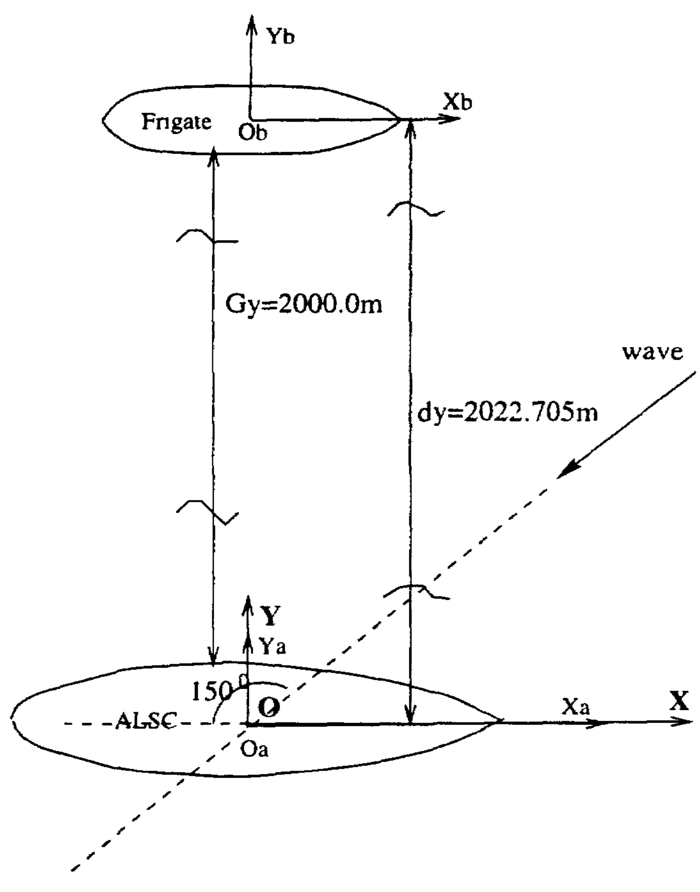
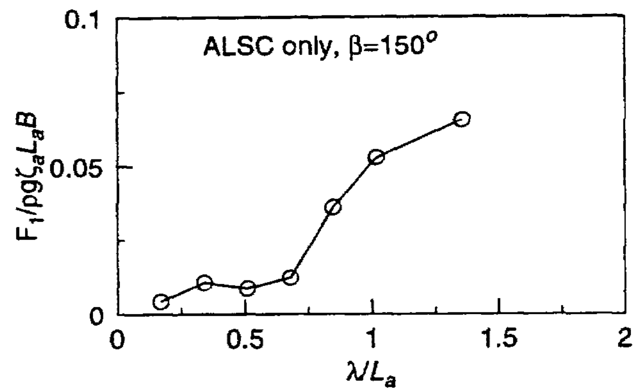
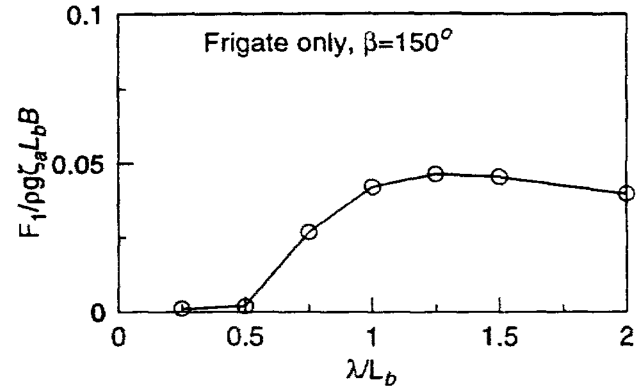


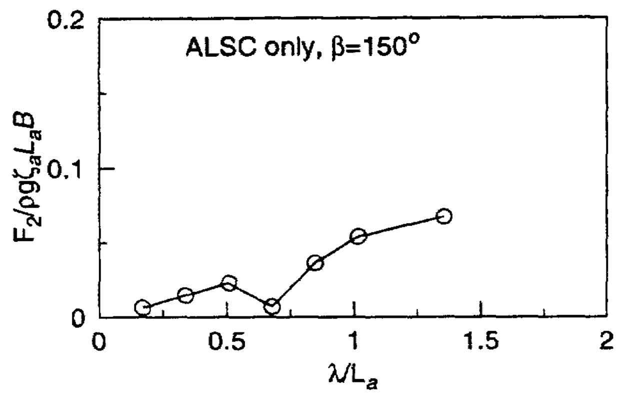
Figure 30: Separation Distance of Two Ships: Gy=2000.0m, dx=0.0m



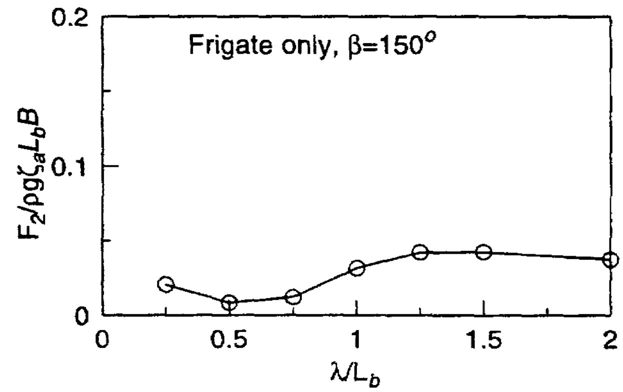
Surge force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



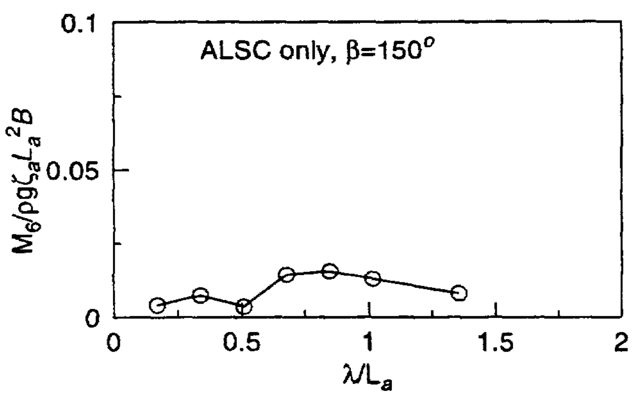
Surge force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



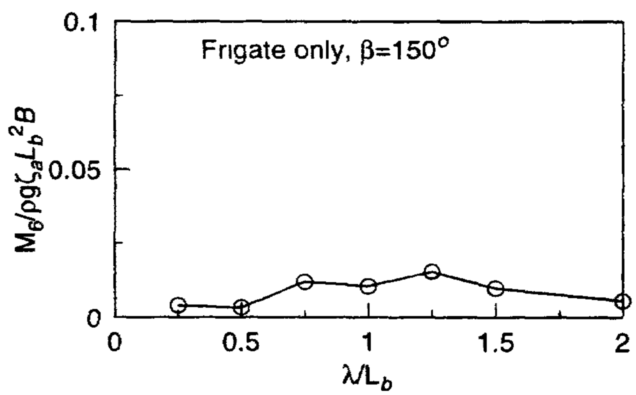
Sway force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

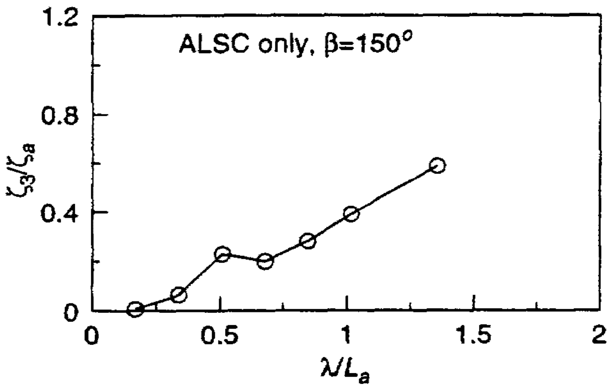


Yaw force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

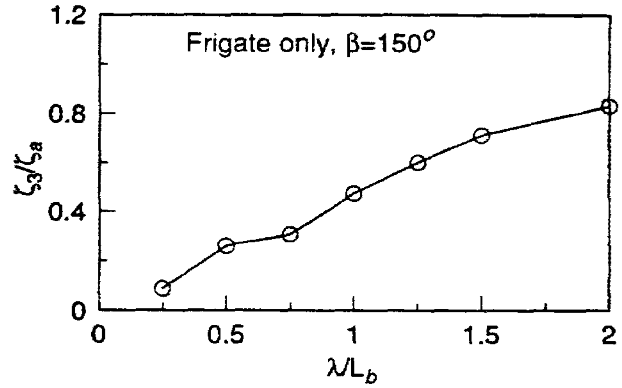


Yaw force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

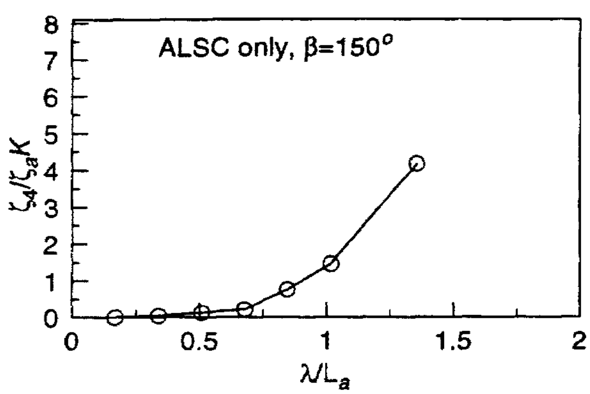
Figure 31: Restraining Forces of Two Ships for Run Set 8-1 and 9-1



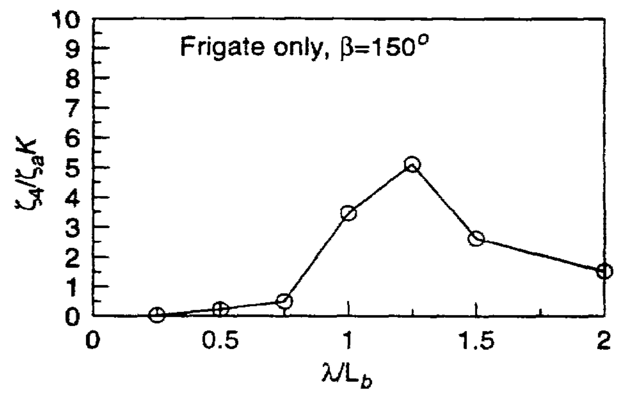
Heave motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



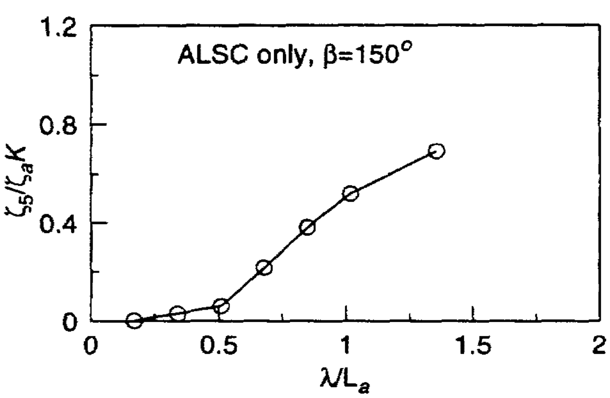
Heave motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



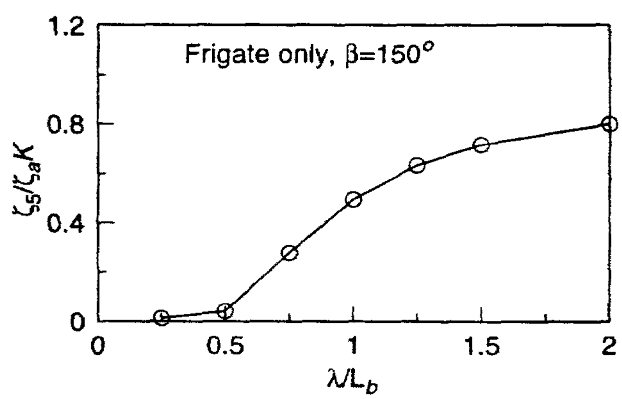
Roll motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

Figure 32: Motion Displacements of Two Ships for Run Set 8-1 and 9-1

5.3.10 Run set 10-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 120^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

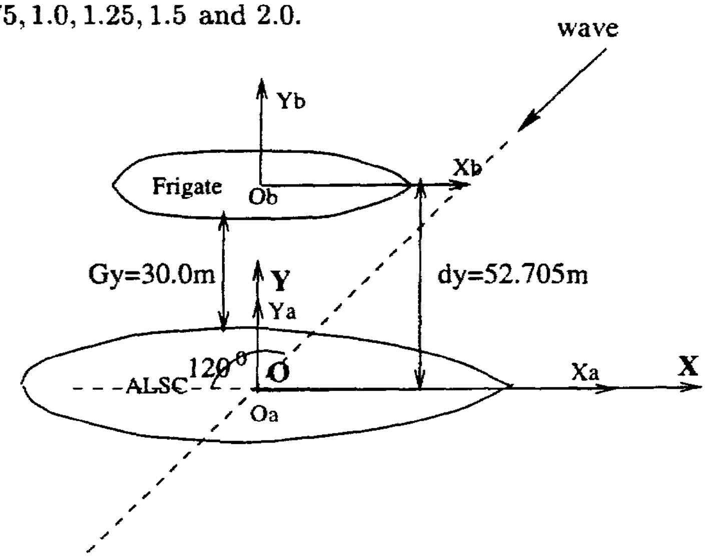
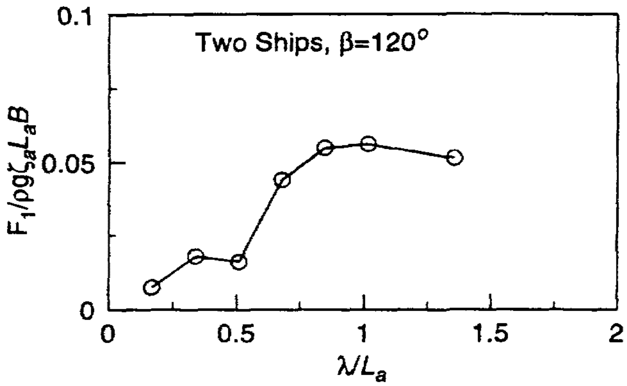
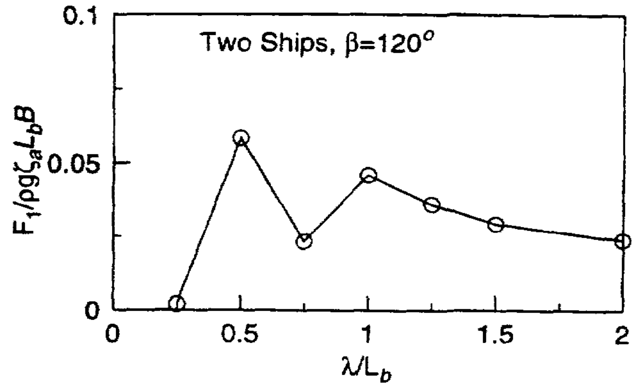


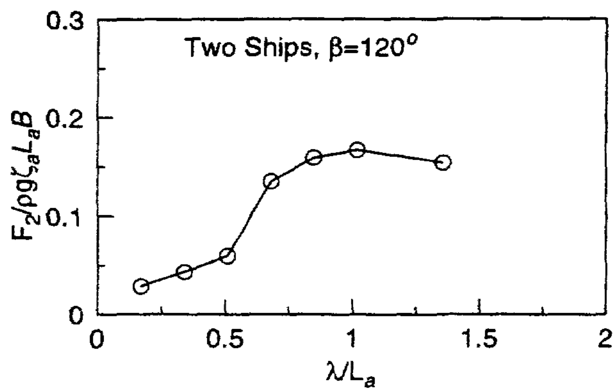
Figure 33: Separation Distance of Two Ships: Gy=30.0m, dx=0.0m



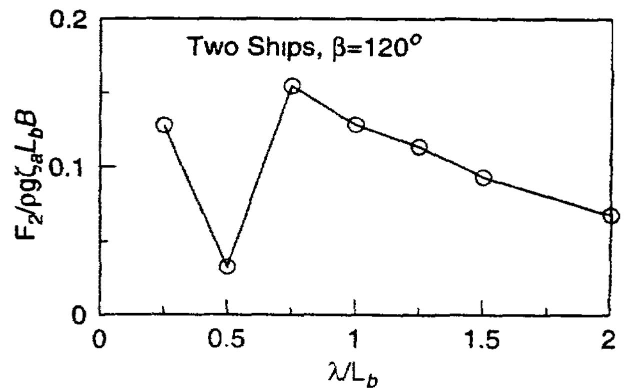
Surge force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



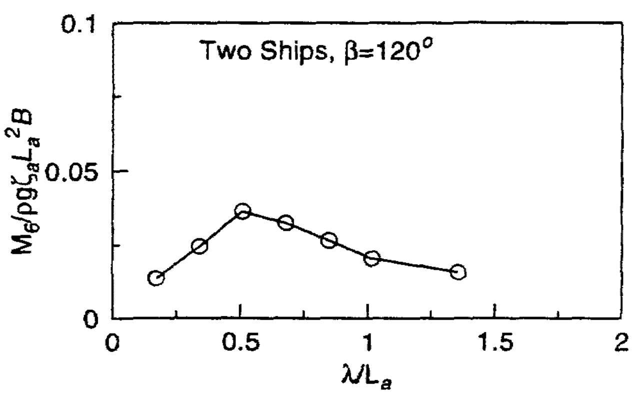
Surge force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



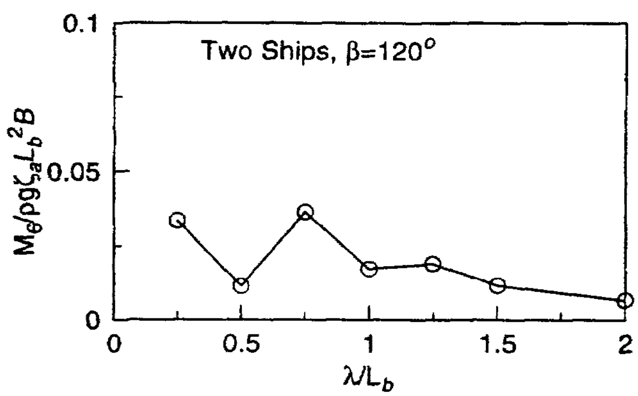
Sway force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

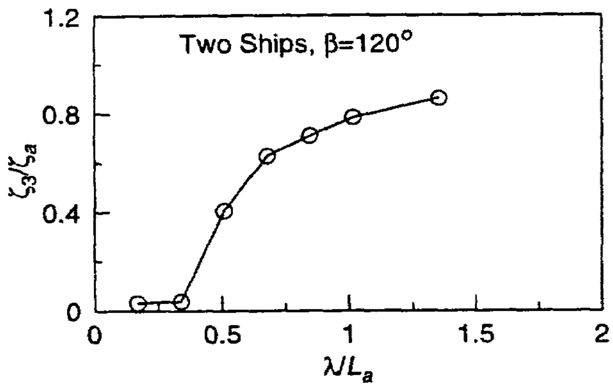


Yaw force on ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s

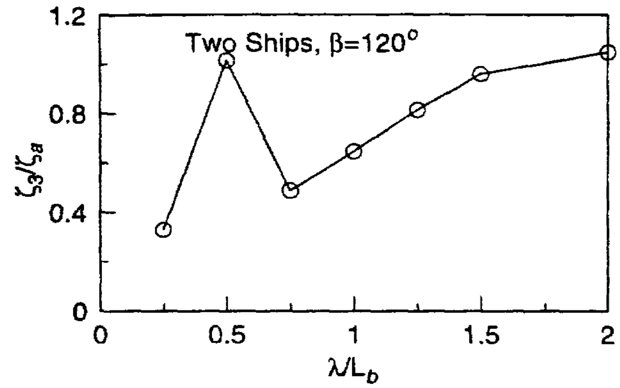


Yaw force on Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

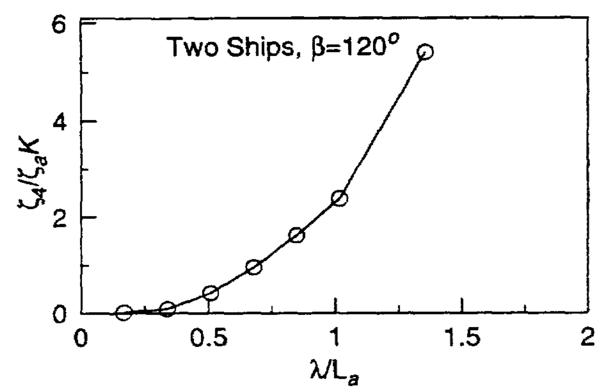
Figure 34: Restraining Forces of Two Ships for Run Set 10-1



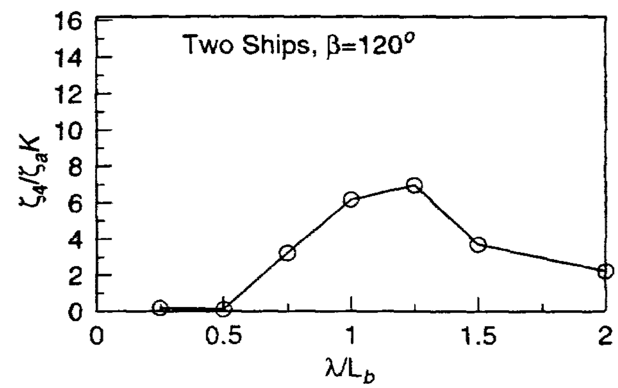
Heave motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



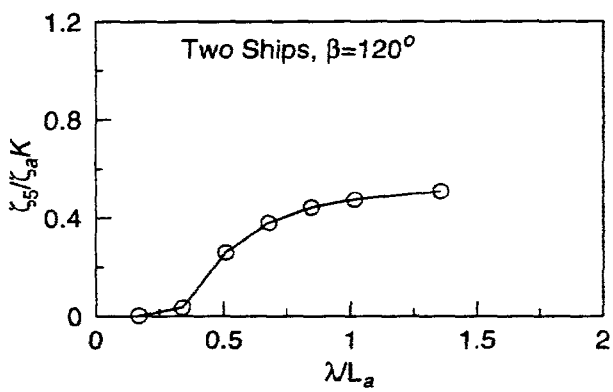
Heave motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



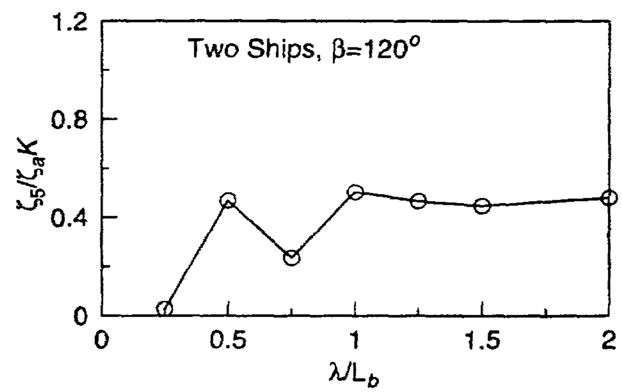
Roll motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=0.0m U=0.0m/s

Figure 35: Motion Displacements of Two Ships for Run Set 10-1

5.3.11 Run set 10-2

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 30.0 m
Longitudinal separation distance dx = 45.0 m
Wave heading angle = 120^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC**:
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

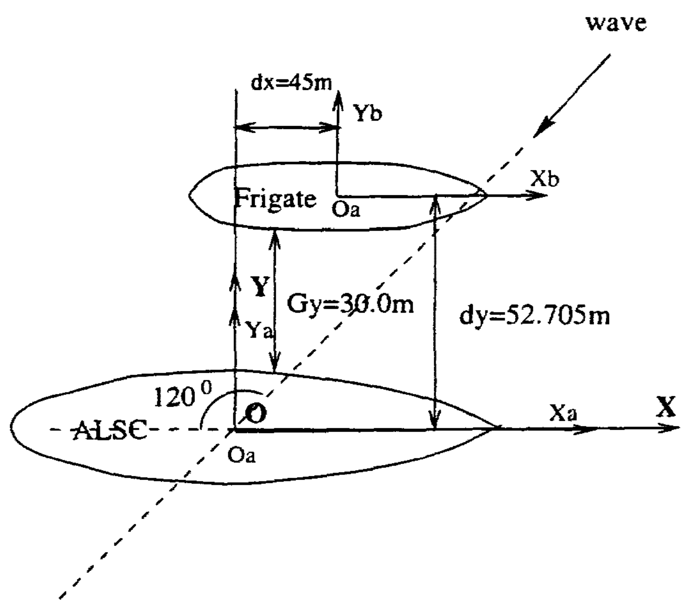
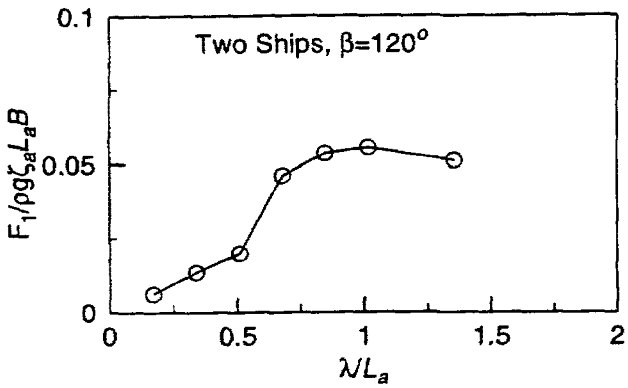
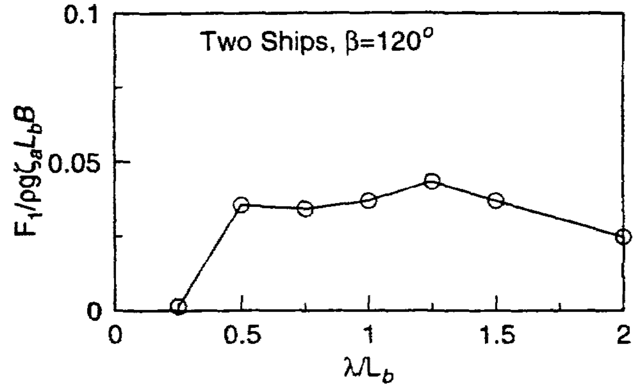


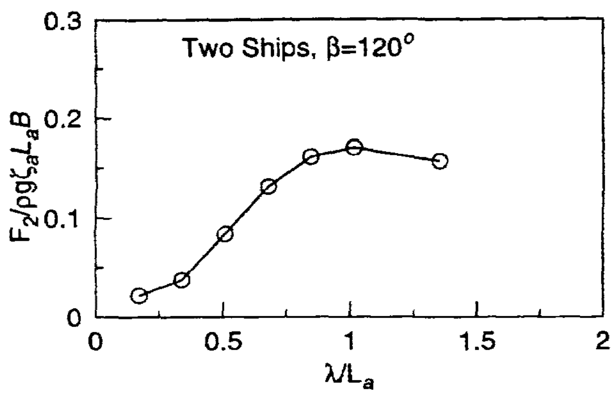
Figure 36: Separation Distance of Two Ships: Gy=30.0m, dx=45.0m



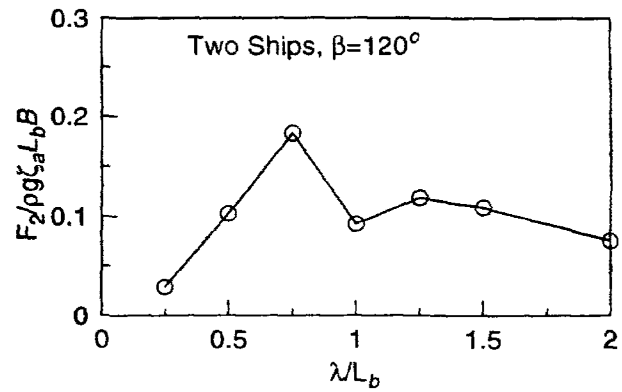
Surge force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



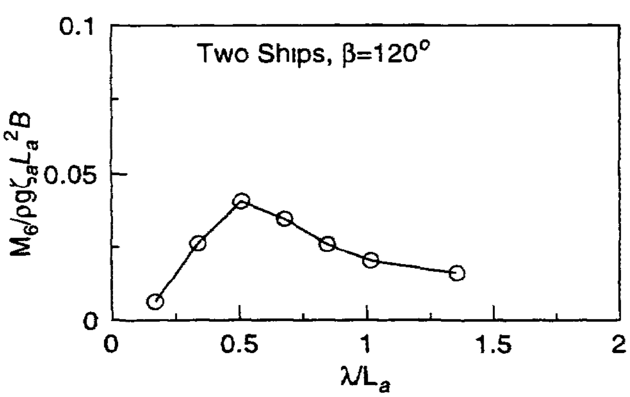
Surge force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



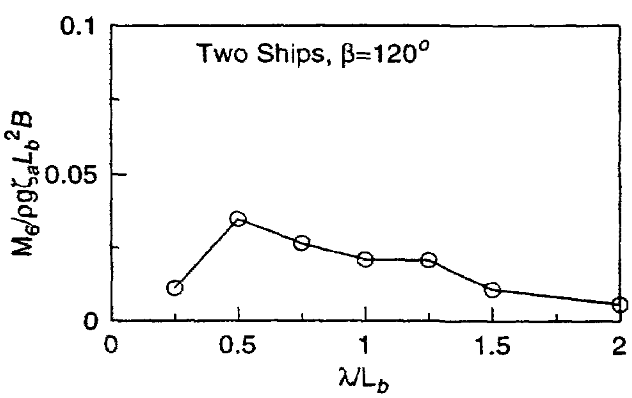
Sway force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

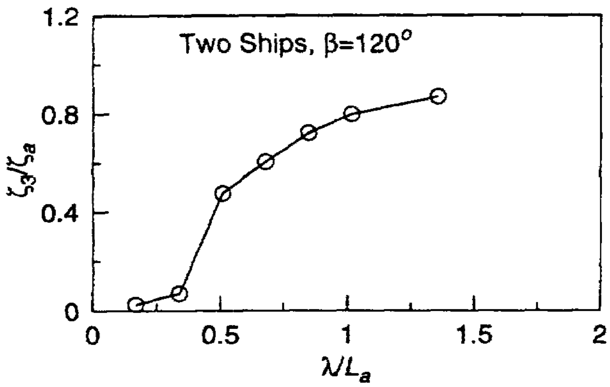


Yaw force on ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s

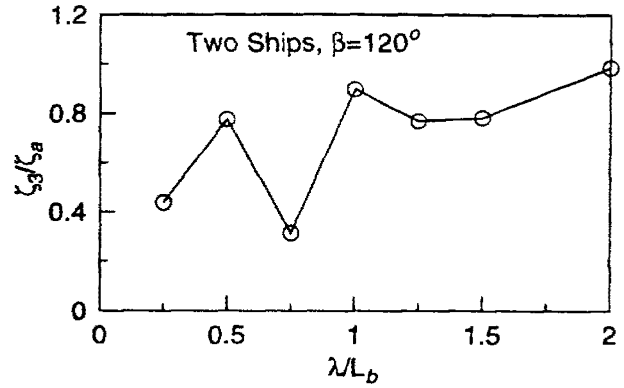


Yaw force on Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

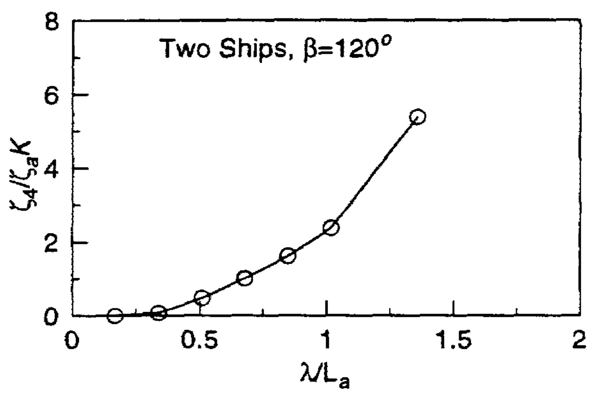
Figure 37: Restraining Forces of Two Ships for Run Set 10-2



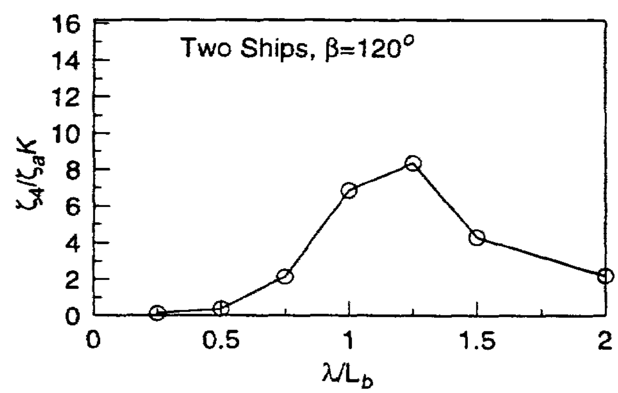
Heave motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



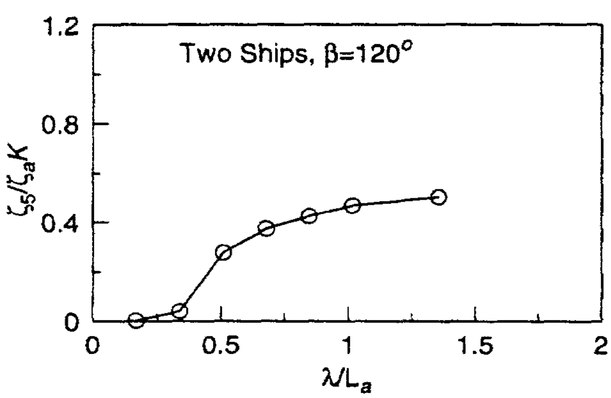
Heave motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



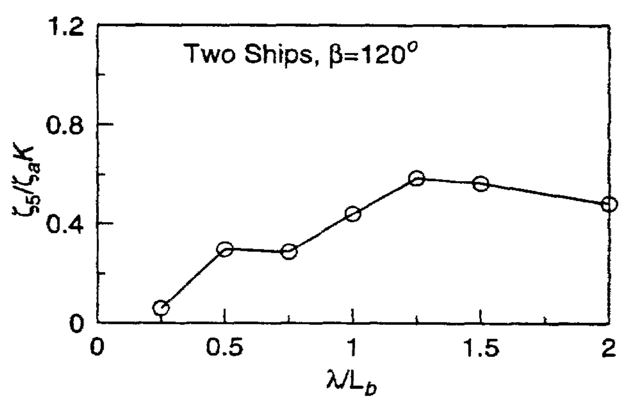
Roll motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=30.0m dx=45.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=30.0m dx=45.0m U=0.0m/s

Figure 38: Motion Displacements of Two Ships for Run Set 10-2

5.3.12 Run set 11-1 and 12-1

condition:

Forward speed U=0.0 knots=0.0 m/s
Lateral separation gap Gy = 2000.0 m
Longitudinal separation distance dx = 0.0 m
Wave heading angle = 120^0
Both ships are restrained in **surge, sway, yaw** during the simulation.
Regular waves:
For **ALSC:**
$\lambda/L_a = 0.169, 0.339, 0.508, 0.678, 0.847, 1.017$ and 1.356.
For **SCAN Frigate:**
$\lambda/L_b = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5$ and 2.0.

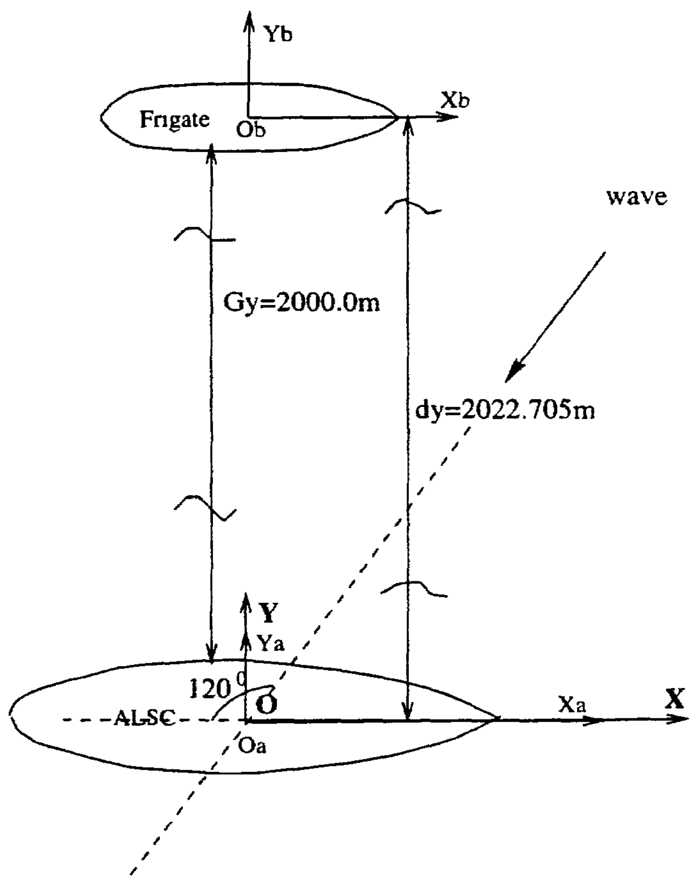
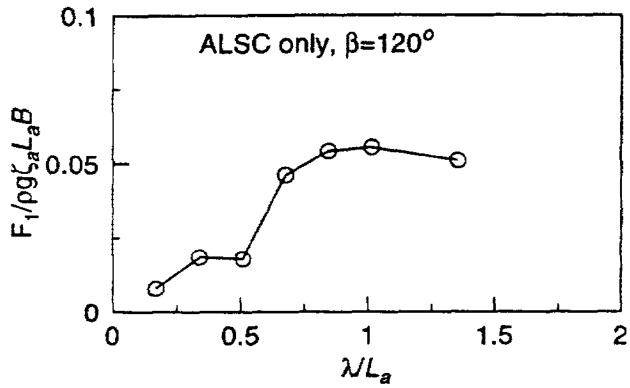
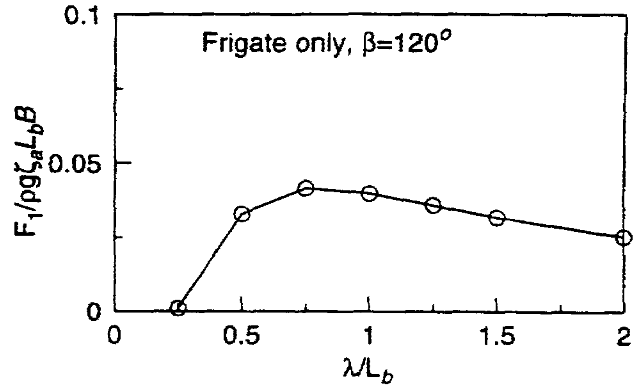


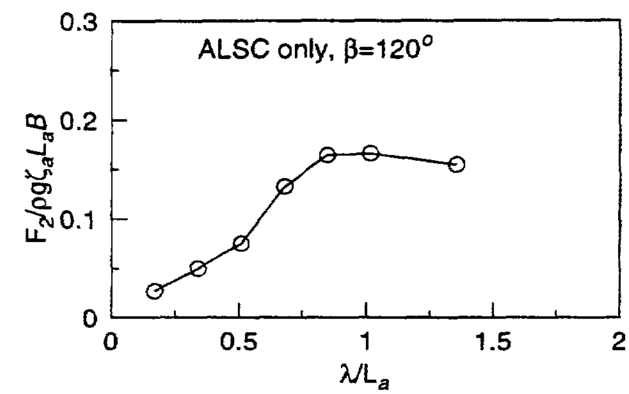
Figure 39: Separation Distance of Two Ships: Gy=2000.0m, dx=0.0m



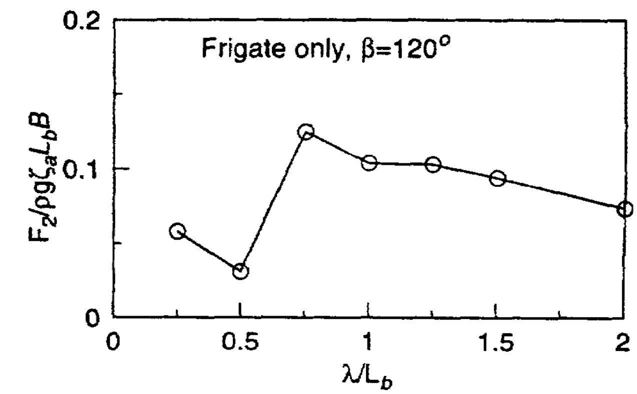
Surge force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



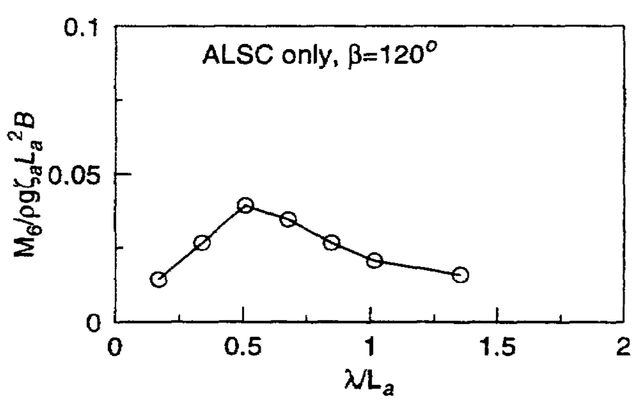
Surge force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



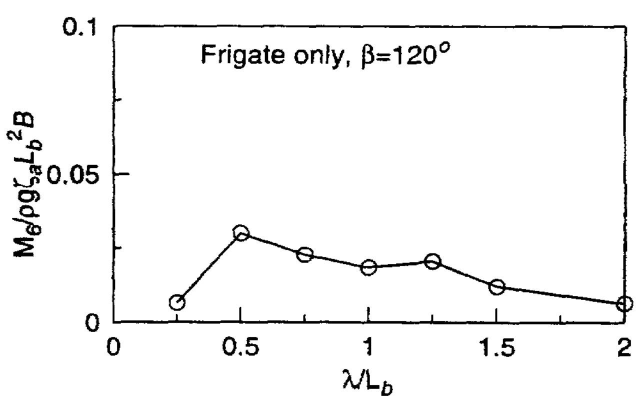
Sway force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Sway force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

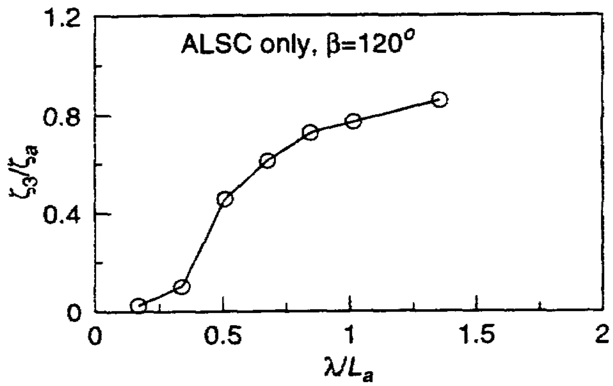


Yaw force on ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

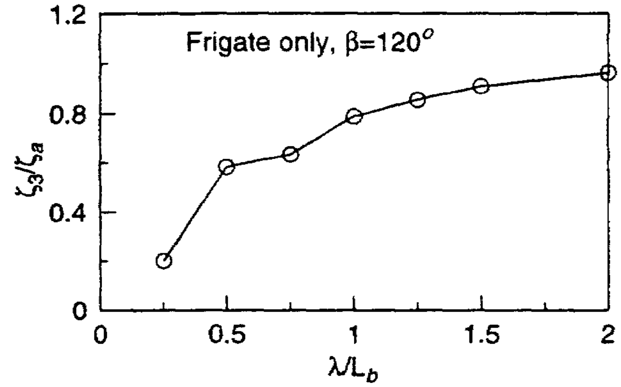


Yaw force on Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

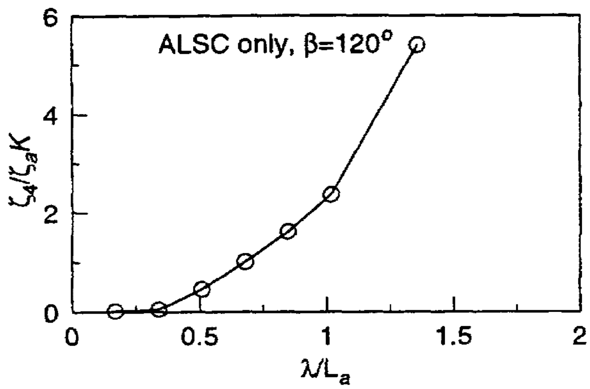
Figure 40: Restraining Forces of Two Ships for Run Set 11-1 and 12-1



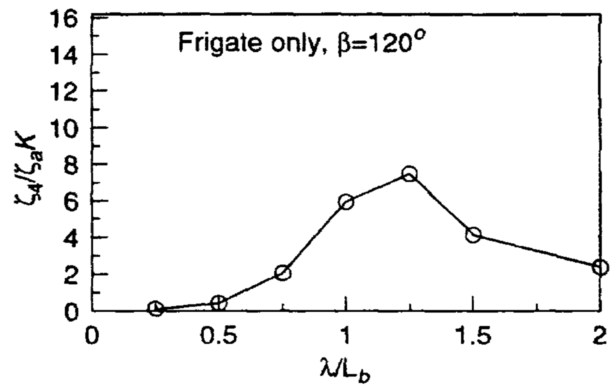
Heave motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



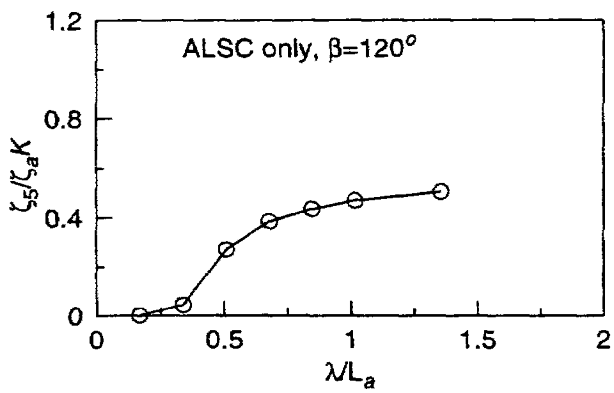
Heave motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



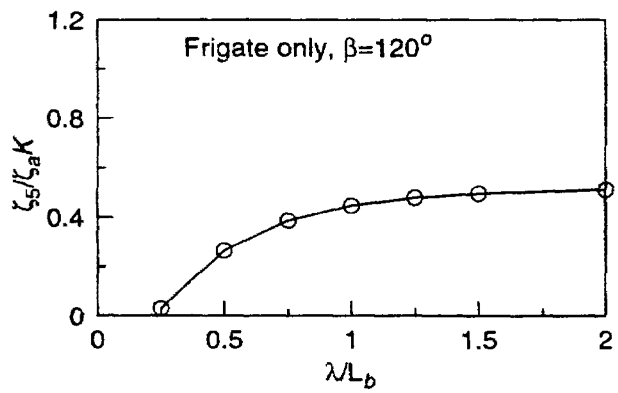
Roll motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Roll motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of ALSC at a separation
Gy=2000.0m dx=0.0m U=0.0m/s



Pitch motion of Frigate at a separation
Gy=2000.0m dx=0.0m U=0.0m/s

Figure 41: Motion Displacements of Two Ships for Run Set 11-1 and 12-1

6 Concluding Remarks

- A modified version of the program SHIPINT, as SHIPINT22, has been developed for numerical seakeeping prediction of the restraining forces and motions of two ships: the ALSC and the SCAN frigate.

- The computed results corresponding to the model test runs are obtained by imposing artificial constraints upon various modes of motions. The computed results show:

  - The roll motions and yaw forces are greater in the case of oblique seas than those for the case of head seas.
  - The roll motion is much greater for $\beta = 120^o$ than that for $\beta = 150^o$ but the pitch is smaller.
  - The interaction motion responses of the ALSC have behavior very close to that of a single ship case, but the interaction motion responses of the SCAN frigate are much different from those of a single ship case.
  - In the case of head seas with forward speed, the pitch motion of the SCAN frigate is greater than the pitch motion without forward speed.
  - The interaction effect on motions decreases with increasing separation distance between the two ships.

- The results presented here are for a set of conditions that will be tested at the Institute of Marine Dynamics. The results of these model tests will provide a validation set against which the performance of SHIPINT22 can be measured.

References

1. C.C. Hsiung and Y.J. He, "Final report on frequency-domain analysis of interaction effects between two ships in waves using the 3-D panel method", Contract Report, DREA CR/96/446, August, 1996.

2. C.C. Hsiung and Y.J. He, "User's guide for SHIPINT - A computer program to compute two ship interaction in waves", Contract Report, DREA CR/96/445, August, 1996.

3. C.C. Hsiung, Y.J. He and X.G. Lu, "User's guide for an automatic panelization program PANELGEN", DREA Contract Report 96/419, 1996.

Appendix A: ALSC Panel Data File

```
264 210
1 90.419998 0.000000 0.000000
2 90.000000 -0.043756 0.000000
3 81.000000 -3.732279 0.000000
4 72.000000 -6.023938 0.000000
5 63.000000 -8.054297 0.000000
6 54.000000 -9.970940 0.000000
7 45.000000 -11.712228 0.000000
8 36.000000 -13.130206 0.000000
9 27.000000 -14.152325 0.000000
10 18.000000 -14.790794 0.000000
11 9.000000 -15.140757 0.000000
12 0.000000 -15.316323 0.000000
13 -9.000000 -15.376906 0.000000
14 -18.000000 -15.336169 0.000000
15 -27.000000 -15.183046 0.000000
16 -36.000000 -14.905368 0.000000
17 -45.000000 -14.486609 0.000000
18 -54.000000 -13.920826 0.000000
19 -63.000000 -13.183241 0.000000
20 -72.000000 -12.127666 -0.000001
21 -81.000000 -10.436591 0.000000
22 -90.000000 -7.784397 0.000000
23 97.064507 0.000000 -1.420000
24 90.000000 -2.155141 -1.932750
25 81.000000 -3.652483 -2.070750
26 72.000000 -5.640112 -2.105500
27 63.000000 -7.499502 -2.118250
28 54.000000 -9.288836 -2.123250
29 45.000000 -10.986279 -2.125000
30 36.000000 -12.512541 -2.125000
31 27.000000 -13.674471 -2.125000
32 18.000000 -14.415432 -2.125000
33 9.000000 -14.817267 -2.125000
34 0.000000 -15.002799 -2.125000
35 -9.000000 -15.032046 -2.125000
36 -18.000000 -14.922239 -2.124750
37 -27.000000 -14.648211 -2.110750
38 -36.000000 -14.229990 -2.052000
39 -45.000000 -13.629851 -1.917250
40 -54.000000 -12.895230 -1.676750
41 -63.000000 -11.987173 -1.331250
42 -72.000000 -10.799935 -0.927501
43 -81.000000 -9.268652 -0.511500
44 -90.000000 -7.294670 -0.125000
45 98.463814 0.000000 -2.840000
46 90.000000 -2.630154 -3.865500
47 81.000000 -3.958067 -4.141500
48 72.000000 -5.412258 -4.211000
49 63.000000 -7.008562 -4.236500
50 54.000000 -8.616744 -4.246500
51 45.000000 -10.243830 -4.250000
52 36.000000 -11.797916 -4.250000
53 27.000000 -13.038542 -4.250000
54 18.000000 -13.863455 -4.250000
55 9.000000 -14.318850 -4.250000
56 0.000000 -14.513623 -4.250000
57 -9.000000 -14.503290 -4.250000
58 -18.000000 -14.300338 -4.249500
59 -27.000000 -13.865146 -4.221500
60 -36.000000 -13.196884 -4.104000
61 -45.000000 -12.266318 -3.834500
62 -54.000000 -11.200510 -3.353500
63 -63.000000 -10.071073 -2.662500
64 -72.000000 -8.924306 -1.855000
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Appendix B: SCAN Frigate Panel Data File

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117	2.513199	-1.585675	-4.214115
118	-2.568096	-1.619489	-4.223486
119	-7.649399	-1.624381	-4.232858
120	-12.730698	-1.579017	-4.242229
121	-17.811996	-1.470034	-4.251600
122	-22.893303	-1.593219	-4.127284
123	-27.974602	-1.820787	-3.988999
124	-33.055893	-1.319206	-3.850714
125	-38.137207	-0.864621	-3.463148
126	-43.218491	-0.6479[illegible]2	-2.679862
127	-48.299797	-0.664984	-1.732515
128	-53.375000	-0.833728	-0.977250
129	-61.000000	-0.318747	-0.318750
130	-60.980003	0.000000	-0.255968
131	59.053799	0.000000	-2.778629
132	58.401402	0.000000	-3.379912
133	53.320099	0.000000	-4.015408
134	48.238800	0.000000	-4.207304
135	43.157501	0.000000	-4.399300
136	38.076199	0.000000	-4.425096
137	32.994900	0.000000	-4.435092
138	27.913601	0.000000	-4.445088
139	22.832302	0.000000	-4.455084
140	17.750999	0.000000	-4.465080
141	12.669701	0.000000	-4.475076

142	7.588402	0.000000	-4.485072
143	2.513199	0.000000	-4.495056
144	-2.568096	0.000000	-4.505052
145	-7.649399	0.000000	-4.515048
146	-12.730698	0.000000	-4.525044
147	-17.811996	0.000000	-4.535040
148	-22.893303	0.000000	-4.402436
149	-27.974602	0.000000	-4.254932
150	-33.055893	0.000000	-4.107428
151	-38.137207	0.000000	-3.694024
152	-43.218491	0.000000	-2.858520
153	-48.299797	0.000000	-1.848016
154	-53.375000	0.000000	-1.042400
155	-61.000000	0.000000	-0.340000
156	-60.980003	0.000000	-0.319960
157	60.947536	0.000000	0.000001
158	58.401402	0.524530	0.000000
159	53.320099	1.476002	0.000000
160	48.238800	2.434710	0.000000
161	43.157501	3.389315	0.000000
162	38.076199	4.303891	0.000000
163	32.994900	5.139366	0.000000
164	27.913601	5.860807	0.000000
165	22.832302	6.436203	0.000000
166	17.750999	6.853822	0.000000
167	12.669701	7.132783	0.000000
168	7.588402	7.296432	0.000000
169	2.513199	7.374531	0.000000
170	-2.568096	7.399031	0.000000
171	-7.649399	7.400450	0.000000
172	-12.730698	7.374021	0.000000
173	-17.811996	7.307408	0.000000
174	-22.893303	7.194063	0.000000
175	-27.974602	7.029663	0.000000
176	-33.055893	6.821264	0.000000
177	-38.137207	6.577001	0.000000
178	-43.218491	6.303737	0.000001
179	-48.299797	6.012887	0.000000
180	-53.375000	5.705189	0.000000
181	-61.000000	2.650257	0.000000
182	-60.984070	0.000000	0.000000
183	60.616665	0.000000	-0.555725
184	58.401402	0.364310	-0.844978
185	53.320099	1.109498	-1.003852
186	48.238800	1.891655	-1.051826
187	43.157501	2.703433	-1.099825
188	38.076199	3.548300	-1.106274
189	32.994900	4.368403	-1.108773
190	27.913601	5.121401	-1.111272
191	22.832302	5.768233	-1.113771
192	17.750999	6.286264	-1.116270
193	12.669701	6.678662	-1.118769
194	7.588402	6.952518	-1.121268
195	2.513199	7.122389	-1.123764
196	-2.568096	7.205325	-1.126263
197	-7.649399	7.218411	-1.128762
198	-12.730698	7.165122	-1.131261
199	-17.811996	7.040945	-1.133760
200	-22.893303	6.856896	-1.100609
201	-27.974602	6.604474	-1.063733
202	-33.055893	6.291186	-1.026857
203	-38.137207	5.981167	-0.923506
204	-43.218491	5.728983	-0.714630
205	-48.299797	5.549915	-0.462004
206	-53.375000	5.454232	-0.260600
207	-61.000000	2.495513	-0.085000
208	-60.981178	0.000000	-0.063992
209	60.272755	0.000000	-1.111451
210	58.401402	0.228421	-1.689956
211	53.320099	0.763709	-2.007704
212	48.238800	1.332298	-2.103652

213	43.157501	1.922484	-2.199650
214	38.076199	2.601648	-2.212548
215	32.994900	3.315800	-2.217546
216	27.913601	4.033416	-2.222544
217	22.832302	4.724860	-2.227542
218	17.750999	5.356009	-2.232540
219	12.669701	5.886914	-2.237538
220	7.588402	6.284518	-2.242536
221	2.513199	6.548412	-2.247528
222	-2.568096	6.688030	-2.252526
223	-7.649399	6.713046	-2.257524
224	-12.730698	6.631817	-2.262522
225	-17.811996	6.436563	-2.267520
226	-22.893303	6.175168	-2.201218
227	-27.974602	5.812051	-2.127466
228	-33.055893	5.341232	-2.053714
229	-38.137207	4.834467	-1.847012
230	-43.218491	4.566773	-1.429260
231	-48.299797	4.641788	-0.924008
232	-53.375000	4.270584	-0.521200
233	-61.000000	2.095455	-0.170000
234	-60.979813	0.000000	-0.127984
235	59.906570	0.000000	-1.667177
236	58.401402	0.123587	-2.534934
237	53.320099	0.443803	-3.011556
238	48.238800	0.759269	-3.155478
239	43.157501	1.041175	-3.299475
240	38.076199	1.427769	-3.318822
241	32.994900	1.876867	-3.326319
242	27.913601	2.389941	-3.333816
243	22.832302	2.977795	-3.341313
244	17.750999	3.616584	-3.348810
245	12.669701	4.225645	-3.356307
246	7.588402	4.727971	-3.363804
247	2.513199	5.092036	-3.371292
248	-2.568096	5.301293	-3.378789
249	-7.649399	5.342615	-3.386286
250	-12.730698	5.234574	-3.393783
251	-17.811996	4.941694	-3.401280
252	-22.893303	4.623424	-3.301827
253	-27.974602	4.131893	-3.191199
254	-33.055893	3.449829	-3.080571
255	-38.137207	2.749537	-2.770518
256	-43.218491	2.456336	-2.143890
257	-48.299797	2.659938	-1.386012
258	-53.375000	2.783313	-0.781800
259	-61.000000	1.375002	-0.255000
260	-60.979912	0.000000	-0.191976
261	59.506714	0.000000	-2.222903
262	58.401402	0.062945	-3.168668
263	53.320099	0.216737	-3.764445
264	48.238800	0.285331	-3.944348
265	43.157501	0.296029	-4.124344
266	38.076199	0.469634	-4.148528
267	32.994900	0.603456	-4.157899
268	27.913601	0.754897	-4.167270
269	22.832302	0.944231	-4.176641
270	17.750999	1.165309	-4.186012
271	12.669701	1.368239	-4.195384
272	7.588402	1.507736	-4.204755
273	2.513199	1.585675	-4.214115
274	-2.568096	1.619489	-4.223486
275	-7.649399	1.624381	-4.232858
276	-12.730698	1.579017	-4.242229
277	-17.811996	1.470034	-4.251600
278	-22.893303	1.593219	-4.127284
279	-27.974602	1.820787	-3.988999
280	-33.055893	1.319206	-3.850714
281	-38.137207	0.864621	-3.463148
282	-43.218491	0.647952	-2.679862
283	-48.299797	0.664984	-1.732515

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312 -60.980003 0.000000 -0.319960
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99 102 128 129 103
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101 105 131 132 106
102 106 132 133 107
103 107 133 134 108
104 108 134 135 109
105 109 135 136 110
106 110 136 137 111
107 111 137 138 112
108 112 138 139 113
109 113 139 140 114
110 114 140 141 115
111 115 141 142 116
112 116 142 143 117
113 117 143 144 118

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117	121	147	148	122
118	122	148	149	123
119	123	149	150	124
120	124	150	151	125
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141	172	173	199	198
142	173	174	200	199
143	174	175	201	200
144	175	176	202	201
145	176	177	203	202
146	177	178	204	203
147	178	179	205	204
148	179	180	206	205
149	180	181	207	206
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152	184	185	211	210
153	185	186	212	211
154	186	187	213	212
155	187	188	214	213
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158	190	191	217	216
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163	195	196	222	221
164	196	197	223	222
165	197	198	224	223
166	198	199	225	224
167	199	200	226	225
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169	201	202	228	227
170	202	203	229	228
171	203	204	230	229
172	204	205	231	230
173	205	206	232	231
174	206	207	233	232
175	207	208	234	233
176	209	210	236	235
177	210	211	237	236
178	211	212	238	237
179	212	213	239	238
180	213	214	240	239
181	214	215	241	240
182	215	216	242	241
183	216	217	243	242
184	217	218	244	243

185	218	219	245	244
186	219	220	246	245
187	220	221	247	246
188	221	222	248	247
189	222	223	249	248
190	223	224	250	249
191	224	225	251	250
192	225	226	252	251
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194	227	228	254	253
195	228	229	255	254
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202	236	237	263	262
203	237	238	264	263
204	238	239	265	264
205	239	240	266	265
206	240	241	267	266
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208	242	243	269	268
209	243	244	270	269
210	244	245	271	270
211	245	246	272	271
212	246	247	273	272
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214	248	249	275	274
215	249	250	276	275
216	250	251	277	276
217	251	252	278	277
218	252	253	279	278
219	253	254	280	279
220	254	255	281	280
221	255	256	282	281
222	256	257	283	282
223	257	258	284	283
224	258	259	285	284
225	259	260	286	285
226	261	262	288	287
227	262	263	289	288
228	263	264	290	289
229	264	265	291	290
230	265	266	292	291
231	266	267	293	292
232	267	268	294	293
233	268	269	295	294
234	269	270	296	295
235	270	271	297	296
236	271	272	298	297
237	272	273	299	298
238	273	274	300	299
239	274	275	301	300
240	275	276	302	301
241	276	277	303	302
242	277	278	304	303
243	278	279	305	304
244	279	280	306	305
245	280	281	307	306
246	281	282	308	307
247	282	283	309	308
248	283	284	310	309
249	284	285	311	310
250	285	286	312	311

Appendix C: Viscous Damping Data for ALSC

```
1      1       1       1       1
21    9    14
999.099976  1.13999999E-06
0.5   0.011
1    73.656   15.557  4.151  0.226
1    194.18   20.93   5.906  1.98
1    234.36   22.594  7.548  3.623
1    261.14   26.298  9.152  5.227
1    291.27   27.78   10.567 6.6422
1    334.8    28.89   11.52  7.585
1    344.84   29.817  12.077 8.152
1    354.89   30.45   12.266 8.34
1    368.28   30.51  12.425  8.5
1    374.976  30.633 12.425  8.5
1    374.976  30.633 12.425  8.5
1    374.976  30.57  12.425  8.5
1    351.54   29.63  12.425  8.5
1    344.844  28.336 12.425  8.5
1    321.408  26.298 12.425  8.5
1    294.624  23.335 12.425  8.495
1    264.492  21.854 12.3    8.375
1    251.1    16     12.28   8.355
1    214.272  12.04  12.26   8.335
1    194.184  7.408  12.07   8.523
1    85.374   0.11   11.51   7.575
4.151   76.   0.     0.     4.5
5.906   66.   0.     0.     9.
7.548   55.   0.     0.     9.
9.152   41.5  0.     0.42   9.
10.567  31.5  0.     1.52   9.0
11.51   25.   0.     2.62   9.0
12.077  18.   0.     3.00   9.
12.266  13.   0.     3.72   9.0
12.425  10.5  10.205 3.72   9.0
12.425  10.5  10.645 3.72   9.0
12.425  10.5  10.846 3.72   9.0
12.425  9.5   10.865 3.72   9.0
12.425  11.0  10.675 3.72   9.0
12.425  14.0  10.252 3.62   9.0
12.425  18.0  0.     2.85   9.0
12.42   20.0  0.     2.50   9.0
12.3    18.0  0.     2.3    9.0
12.28   15.0  0.     2.0    9.0
12.26   11.0  0.     1.9    9.0
12.07   0.01  0.     1.8    9.0
11.51   0.01  0.     0.0    4.5
0.      0.    0.      0.
0.      0.    0.566   0.
0.      0.    0.755   0.
0.      0.    0.86    0.
0.      0.    0.944   0.
0.      0.    0.90   0.
0.      0.    0.89   0.
0.      0.    0.89   0.
0.471   7.    0.83   0.
0.471   7.5   0.83   0.
0.471   7.719 0.83   0.
0.471   7.719 0.83   0.
0.471   7.6   0.83   0.
0.471   7.    0.85   0.
0.      0.    0.99   0.
0.      0.    1.15   0.
0.      0.    1.23   0.
0.      0.    1.90   0.
0.      0.    2.5    0.
0.      0.    3.02   0.
0.      0.    0.     0.
0.   3.925  5.4  0.   27.0
2   1.17
9.0
8.3
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90.0
5.0
5.0
5.4
-9.0
8.3
-90.0
5.0
5.0
5.4

Appendix D: Viscous Damping Data for SCAN Frigate

```
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25   9   15
999.099976  1.13999999E-06
0.8   0.026
1   14.3   4.95   2.251   0.196
1  55.17  11.26   2.975   0.92
1  51.78  11.90   3.775   1.72
1  57.35  12.55   4.789   2.744
1   62.53  13.16   5.665   3.61
1  72.88  13.68   6.095   4.04
1  73.68  14.10   6.230   4.175
1  76.87  14.47   6.385   4.33
1  80.45  14.68   6.555   4.50
1  82.84  14.783  6.555   4.50
1  82.85  14.783  6.555   4.50
1  82.85  14.783  6.555   4.50
1  80.05  14.783  6.555   4.50
1  77.26  14.65   6.555   4.50
1  76.86  14.37   6.555   4.50
1  70.10  13.84   6.555   4.50
1  67.30  13.00   6.555   4.50
1  66.51  11.84   6.555   4.50
1  60.14  10.47   6.555   4.50
1  53.37  8.84    6.555   4.50
1  51.97  7.00    6.555   4.50
1  47.75  5.05    6.315   4.26
1  43.41  3.00    6.105   4.05
1  42.59  1.16    5.505   3.45
1  15.00  0.01    2.065   0.01
2.251  45.  0.  0.98     3.81
2.975  43.  0.  1.38     6.35
3.775  43.  0.  1.78     5.08
4.789  43.  0.  2.18     5.08
5.665  43.  0.  2.58     5.08
6.095  40.  0.  2.98     5.08
6.230  35.  0.  3.38     5.08
6.385  30.  0.  3.78     5.08
6.555  28.  4.185   4.18  5.08
6.555  20.  4.385   4.59  5.08
6.555  20.  4.487   4.59  5.08
6.555  20.  4.72    4.59  5.08
6.555  13.  4.795   4.184 5.08
6.555  19.  4.475   3.784 5.08
6.555  26.  4.375   3.384 5.08
6.555  29.  0.      0.1   5.08
6.555  35.  0.      0.1   5.08
6.555  39.  0.      0.1   5.08
6.555  40.  0.      0.1  5.08
6.555  40.  0.      0.1  5.08
6.555  40.  0.      0.1  5.08
6.315  35.  0.      0.1  5.08
6.105  23.  0.      0.1  5.08
5.505  10.  0.      0.1  6.39
2.065  0.1  0.      0.1  3.85
0.     0.   0.23  0.
0.     0.   0.39  0.
0.     0.   1.25  0.
0.     0.   2.30  0.
0.     0.   1.85  0.
0.     0.   1.18  0.
0.     0.   1.95  0.
0.     0.   1.22  0.
0.484  4.4  1.22  0.
0.484  4.6  1.22  0.
0.484  4.8  1.33  0.
0.484  4.95 1.22  0.
0.484  5.15 1.22  0.
0.484  5.20 1.22  0.
0.484  5.25 1.45  0.
0.     0.   1.67  0.
0.     0.   1.82  0.
```

```
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
      0.      0.    0.     0.
 2.5    2.055   5.3   1.02    25.97
 9  1.17
 3.5  2.9  97.  0.5  0.5  2.0
 -3.5 2.9 -97.  0.5  0.5  2.0
 1.9  2.3   47.  0.5   0.5   2.0
-1.9  2.3  -47.  0.5   0.5   2.0
 4.1  3.6   104.   1.0   1.0  3.3
-4.1  3.6  -104.   1.0   1.0  3.3
 1.0  2.9   48.  1.0  1.0  3.4
-1.0  2.9  -48.  1.0  1.0  3.4
 0.0  4.5  90.   4.95  4.95   1.16
```

Appendix E: Wave Input Data

3
5.0 12.4

Appendix F: The Output Sample of Run Set 4-1

```
***************************************
 SHIPINT Program Output Results
***************************************
Date of Computation:
Dec. 6, 1999

Form of ship_a:
ALSC
panel file : alsc.panel
Ship_a geometrical principals:
L=  180.00(m.) B=  30.63(m.) T=  8.50(m.) Vol=  27535.00(m.^3) Cb= 0.59
Xg= -1.69(m.)Yg=  0.00(m.)Zg=  3.92(m.)
r144=   8.05(m.) r155=   45.00(m.) r166=   45.00(m.)
Control parameters in six degree of motion:
 1.  1.  0.  0.  0.  1.

Form of ship_b:
SCAN
panel file : scan.panel
Ship_b geometrical principals:
L=  122.00(m.) B=  14.78(m.) T=  4.50(m.) Vol=   3925.54(m.^3) Cb= 0.48
Xg=  3.28(m.)Yg=  0.00(m.)Zg=  2.06(m.)
r144=   4.92(m.) r155=   30.50(m.) r166=   30.50(m.)
Control parameters in six degree of motion:
 1.  1.  0.  0.  0.  1.

Separation distance:
          Lateral gap=    30.00(m.)   Dy=   52.705(m.)   Dx=     0.00(m.)

ship speed:   0.000(m/s)

number of wave heading angles:  1
no. heading(Deg.)
1  180.

number of wave length to ship length ratios:  7
no. Lambda/Lb
 1     0.25
 2     0.50
 3     0.75
 4     1.00
 5     1.25
 6     1.50
 7     2.00

control parameters for viscous damping and m-term:  1  1
```

nondimensional wave exciting forces on ship_a (Heading = 180.0 (Deg.)

no.	Lamda/La	f1	f2	f3	f4	f5	f6
1	0.16944	0.00435	0.02417	0.03000	0.00017	0.00510	0.00374
2	0.33889	0.00692	0.02330	0.03907	0.00031	0.00486	0.00342
3	0.50833	0.00884	0.02813	0.04536	0.00103	0.00417	0.01071
4	0.67778	0.01892	0.06136	0.05175	0.00084	0.03534	0.00723
5	0.84722	0.03016	0.05908	0.13172	0.00046	0.04767	0.00347
6	1.01667	0.03846	0.04377	0.16210	0.00030	0.05874	0.00215
7	1.35556	0.04674	0.02756	0.23938	0.00017	0.07220	0.00094

phase angle (Deg.)of wave exciting forces on ship_a:(rel to wave crest at ship_a CG)

no.	Lamda/La	pf1	pf2	pf3	pf4	pf5	pf6
1	0.169	72.517	45.253	-153.332	32.070	-4.196	33.980
2	0.339	-41.267	-77.642	65.324	153.839	-174.674	-117.434
3	0.508	177.201	-152.197	-112.247	-76.561	-83.446	-63.912

4	0.678	4.759	-116.624	50.562	7.596	-33.262	2.132
5	0.847	-26.752	-72.190	72.800	53.681	-50.469	15.109
6	1.017	-46.948	-51.340	60.180	81.162	-63.383	25.028
7	1.356	-68.177	-31.258	36.348	116.531	-75.080	27.964

nondimensional wave exciting forces on ship_b (Heading = 180.0 (Deg.)

no.	Lamda/Lb	f1	f2	f3	f4	f5	f6
1	0.25000	0.00624	0.04001	0.06078	0.00004	0.01024	0.00701
2	0.50000	0.00760	0.02333	0.07137	0.00020	0.01451	0.00044
3	0.75000	0.02333	0.02232	0.02057	0.00043	0.06369	0.00926
4	1.00000	0.03598	0.05165	0.26809	0.00068	0.09368	0.00933
5	1.25000	0.03641	0.05193	0.36730	0.00048	0.08494	0.00540
6	1.50000	0.03569	0.03874	0.38422	0.00033	0.08203	0.00351
7	2.00000	0.03246	0.02496	0.43588	0.00021	0.07667	0.00182

phase angle (Deg.)of wave exciting forces on ship_b:(rel to wave crest at ship_b CG)

no.	Lamda/Lb	pf1	pf2	pf3	pf4	pf5	pf6
1	0.250	8.798	-178.195	166.632	-84.254	-0.031	-179.140
2	0.500	78.201	-96.300	-172.638	-43.908	76.688	160.676
3	0.750	-74.563	38.442	47.397	156.783	-82.030	156.943
4	1.000	-68.791	75.804	17.564	-132.760	-61.675	-146.261
5	1.250	-76.275	121.836	32.804	-88.074	-61.967	-119.484
6	1.500	-81.346	141.231	29.771	-68.604	-64.615	-106.477
7	2.000	-87.797	155.889	20.760	-48.342	-64.550	-88.452

nondimensional transfer function: motion dispt. amplitudes on ship_a

Heading = 180.0 (Deg.)

no.	Lamda/La	y1/a	y2/a	y3/a	y4/ka	y5/ka	y6/ka
1	0.169	0.00000	0.00000	0.01014	0.00040	0.00132	0.00000
2	0.339	0.00000	0.00000	0.04159	0.01896	0.01947	0.00000
3	0.508	0.00000	0.00000	0.23734	0.05649	0.07191	0.00000
4	0.678	0.00000	0.00000	0.17975	0.04559	0.11370	0.00000
5	0.847	0.00000	0.00000	0.19954	0.05771	0.28412	0.00000
6	1.017	0.00000	0.00000	0.28016	0.05503	0.46127	0.00000
7	1.356	0.00000	0.00000	0.47732	0.08402	0.70705	0.00000

phase angle(Deg.) of motions of ship_a:(rel to wave crest at ship_a CG)

Heading = 180.0 (Deg.)

no.	Lamda/La	pm1	pm2	pm3	pm4	pm5	pm6
1	0.169	0.000	0.000	56.983	-109.334	178.104	0.000
2	0.339	0.000	0.000	-144.730	-26.587	32.447	0.000
3	0.508	0.000	0.000	148.378	155.990	-14.191	0.000
4	0.678	0.000	0.000	110.581	-106.630	-87.472	0.000
5	0.847	0.000	0.000	58.432	-58.669	-107.596	0.000
6	1.017	0.000	0.000	30.264	-14.823	-108.804	0.000
7	1.356	0.000	0.000	8.050	31.420	-103.777	0.000

nondimensional transfer function: motion dispt. amplitudes on ship_b

Heading = 180.0 (Deg.)

no.	Lamda/Lb	y1/a	y2/a	y3/a	y4/ka	y5/ka	y6/ka
1	0.250	0.00000	0.00000	0.13572	0.02126	0.02161	0.00000

2	0.500	0.00000	0.00000	0.26403	0.14992	0.08678	0.00000
3	0.750	0.00000	0.00000	0.13272	0.58785	0.24726	0.00000
4	1.000	0.00000	0.00000	0.48499	2.01714	0.46382	0.00000
5	1.250	0.00000	0.00000	0.61457	2.08053	0.58794	0.00000
6	1.500	0.00000	0.00000	0.68982	0.66711	0.70614	0.00000
7	2.000	0.00000	0.00000	0.77926	0.19465	0.87105	0.00000

phase angle(Deg.) of motions of ship_b:(rel to wave crest at ship_b CG)

Heading = 180.0 (Deg.)

no.	Lamda/Lb	pm1	pm2	pm3	pm4	pm5	pm6
1	0.250	0.000	0.000	47.120	63.098	-117.268	0.000
2	0.500	0.000	0.000	121.974	131.194	-2.132	0.000
3	0.750	0.000	0.000	20.926	0.910	-115.101	0.000
4	1.000	0.000	0.000	20.888	91.910	-108.434	0.000
5	1.250	0.000	0.000	16.127	-109.674	-110.070	0.000
6	1.500	0.000	0.000	12.254	-59.765	-110.770	0.000
7	2.000	0.000	0.000	6.422	-16.438	-107.459	0.000

nondimensional measurement forces on ship_a (Heading = 180.0 (Deg.)

no.	Lamda/La	f1	f2	f3	f4	f5	f6
1	0.16944	0.00550	0.01383	0.00000	0.00000	0.00000	0.00276
2	0.33889	0.00928	0.00791	0.00000	0.00000	0.00000	0.00244
3	0.50833	0.00515	0.01098	0.00000	0.00000	0.00000	0.00551
4	0.67778	0.00366	0.00748	0.00000	0.00000	0.00000	0.00243
5	0.84722	0.02113	0.00622	0.00000	0.00000	0.00000	0.00133
6	1.01667	0.04222	0.00274	0.00000	0.00000	0.00000	0.00065
7	1.35556	0.06444	0.00084	0.00000	0.00000	0.00000	0.00017

phase angle (Deg.)of measurement forces on ship_a:(rel to wave crest at ship_a CG)

no.	Lamda/La	pf1	pf2	pf3	pf4	pf5	pf6
1	0.169	100.766	77.549	0.000	0.000	0.000	74.016
2	0.339	-32.749	60.908	0.000	0.000	0.000	-129.008
3	0.508	177.692	127.798	0.000	0.000	0.000	16.646
4	0.678	7.721	-173.333	0.000	0.000	0.000	103.772
5	0.847	-80.944	-130.006	0.000	0.000	0.000	148.346
6	1.017	-89.639	-103.441	0.000	0.000	0.000	-175.730
7	1.356	-90.154	-86.847	0.000	0.000	0.000	-136.065

nondimensional measurement forces on ship_b (Heading = 180.0 (Deg.)

no.	Lamda/Lb	f1	f2	f3	f4	f5	f6
1	0.25000	0.00131	0.02428	0.00000	0.00000	0.00000	0.00804
2	0.50000	0.00956	0.01893	0.00000	0.00000	0.00000	0.00210
3	0.75000	0.02348	0.04296	0.00000	0.00000	0.00000	0.00440
4	1.00000	0.03847	0.02328	0.00000	0.00000	0.00000	0.00196
5	1.25000	0.04187	0.02007	0.00000	0.00000	0.00000	0.00429
6	1.50000	0.04385	0.01127	0.00000	0.00000	0.00000	0.00185
7	2.00000	0.04287	0.00412	0.00000	0.00000	0.00000	0.00064

phase angle (Deg.)of measurement forces on ship_b:(rel to wave crest at ship_b CG)

no.	Lamda/Lb	pf1	pf2	pf3	pf4	pf5	pf6
1	0.250	40.169	-155.968	0.000	0.000	0.000	-147.990

2	0.500	19.209	-166.942	0.000	0.000	0.000	-106.296
3	0.750	-108.443	7.436	0.000	0.000	0.000	179.303
4	1.000	-100.740	65.558	0.000	0.000	0.000	-164.787
5	1.250	-103.447	87.322	0.000	0.000	0.000	-91.905
6	1.500	-105.248	112.422	0.000	0.000	0.000	-46.712
7	2.000	-103.144	139.238	0.000	0.000	0.000	2.406

RMS displacements and accelerations of ship-a
(Heading= 180.0(Deg.), Bretschneider Spectrum
average period T1=12.4(sec), HS=5(m)

---

motion_mode j	Dj	Aj
1	0.0000(m)	0.0000(g)
2	0.0000(m)	0.0000(g)
3	0.2154(m)	0.0080(g)
4	0.1017(deg)	0.0548(deg/s^2)
5	0.5627(deg)	0.1874(deg/s^2)
6	0.0000(deg)	0.0000(deg/s^2)

RMS displacements and accelerations of ship-b
(Heading= 180.0(Deg.), Bretschneider Spectrum
average period T1=12.4(sec), HS=5(m)

---

motion_mode j	Dj	Aj
1	0.0000(m)	0.0000(g)
2	0.0000(m)	0.0000(g)
3	0.4512(m)	0.0174(g)
4	2.4056(deg)	1.1653(deg/s^2)
5	0.9468(deg)	0.3887(deg/s^2)
6	0.0000(deg)	0.0000(deg/s^2)

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Numerical Seakeeping Predictions Including Interaction Effects between Two Ships

4 AUTHORS (Last name, first name, middle initial. If military, show rank, e g Doe, Maj John E.)

Li, L., He, Y.J. and Hsiung, C.C.

5 DATE OF PUBLICATION (month and year of publication of document) April 2000	6a NO OF PAGES (total containing information Include Annexes, Appendices, etc) 102	6b NO. OF REFS (total cited in document) 3

7 DESCRIPTIVE NOTES (the category of the document, e g technical report, technical note or memorandum If appropriate, enter the type of report, e g interim, progress, summary, annual or final Give the inclusive dates when a specific reporting period is covered)

CONTRACTOR REPORT

8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development Include address)
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9a PROJECT OR GRANT NO (if appropriate, the applicable research and development project or grant number under which the document was written Please specify whether project or grant) Project 1gb22	9b. CONTRACT NO (if appropriate, the applicable number under which the document was written) W7707-8-6038/001
10a ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity This number must be unique to this document)	10b OTHER DOCUMENT NOs (Any other numbers which may be assigned this document either by the originator or by the sponsor) DREA CR 2000-050

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A modified version of the SHIPINT program, SHIPINT2, has been developed to compute the restraining forces and motions of the two ship interaction problem in accordance with prescribed captive model test conditions. The coupled motions are computed using a three-dimensional panel method with zero forward speed Green's function and a simple forward speed correction. With this method, the field points and source points are distributed on the wetted surface of two ships (ship-a and ship-b). The unsteady hydrodynamic forces, wave exciting forces and coupled motion amplitudes are computed based on the two ships interacting. Two ship double-body flow is used to determine the steady flow disturbance potential and velocity distribution. In this computation, the m-term computation is performed by the integral equation method based on the double body flow of two ships interacting. Alternatively, with the uniform flow assumption, the approximate m-terms can also be used in this study. Schmitke's method is applied to compute the viscous roll damping coefficients for ship-a and ship-b separately. The viscous interaction between the two ships is neglected. Spectral analyses for irregular waves are also carried out for ship-a and ship-b.

Calculations have been carried out in regular waves with heading angles of 120, 150, and 180 degrees for two forward speeds of 12 knots and 0 knots. Also considered is a lateral separation distance of 52.705 m, and a longitudinal separation distance $d_x/L_{ALSC} = 0.25$. Ship motions in irregular waves, using the Bretschneider spectrum for Sea State 6 ($H_s = 5.0$ m, $T_p = 12.4$ s), have also been computed.

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frequency domain
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